Chapter 8

Fresh and Hardened Concrete

FRESH AND HARDENED CONCRETE

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1. GENERAL

The properties of a building material are of great importance with respect to the function for which the building was intended. Besides the required load capacity and durability, which are the main conditions, a building must protect against cold, heat, rain, wind, etc. A comfortable and pleasant living atmosphere should be created, which cannot be achieved simply by the design of the building or the application of the specific material, but by the favorable combination of several materials. The correct choice of material, however, can only be made if everybody involved with the construction has good knowledge of the material properties.

The properties of building materials such as bricks and steel will remain unchanged throughout the building process, while the final properties of concrete will only become established after placing. Cement is only an intermediate product of a building material.

New developments in concrete technology and building technique, based on many years of research, have made it possible to build such constructions as the 550 m tall TV tower in Toronto, prestressed concrete bridges with a span of up to 240 m and drilling platforms in the ocean. Flowing concrete has changed the method of placing. So far, concrete has been able, in most cases, to compete with other building materials.

All of these constructions and techniques have been made possible by the improvement of cement quality and on the methods of its application. Should further material requirements arise, would it be possible to adapt the concrete properties? Can the cement manufacturer contribute? He should at least make an attempt to meet any new requirements, because each successful concrete construction will favorably affect the cement production.

On the other hand, the cement manufacturer must be able to defend himself if defects in concrete are unjustly attributed to the cement. He can only be persuasive if he has thorough knowledge of concrete properties and concrete technology.

2. DEFINITION

2.1 Defintion of concrete

ACI has defined concrete as follows:

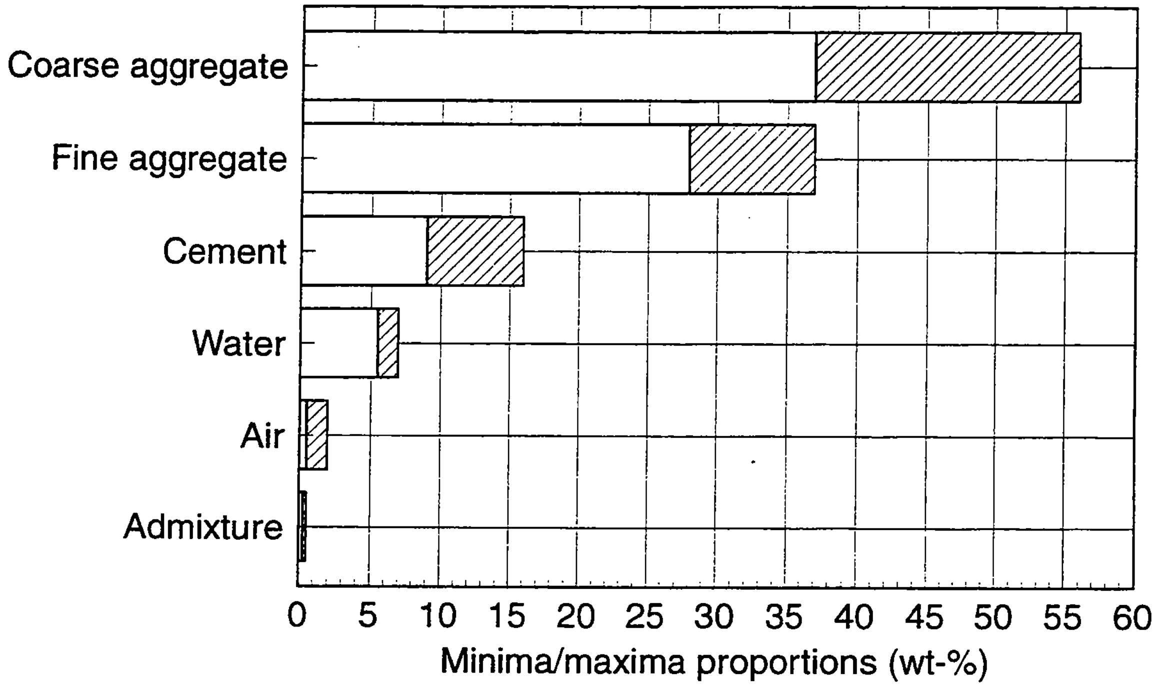
Concrete is a composite material
consisting essentially of a binding medium,
within which particles or fragments of aggregate are embedded.

In Portland cement concrete, the binder is a mixture of Portland cement and water.

2.2 Composition of concrete

Fig. 1: Range of Proportions of materials used in concrete (by weight)

Stages of concrete



The properties of concrete depend very much on its age. Roughly three stages can be distinguished.

Fresh concrete
(a workable mass)

⇩

Transition
through intermediate stages
(sometimes called 'green' or 'young' concrete)

⇩

Hardened concrete
(an artificial stone which has reached the required properties for a specific structure)

The transition from fresh to hardened concrete is a continuous process during which it changes from a workable mass to an artificial stone. The performance of the concrete at certain ages has a great influence on its applicability, and, therefore, it is of interest to know the concrete properties not only when placed (fresh) or used (hardened), but sometimes also during the entire development.

2.3 Green and young concrete, workability and resistance to loading of concrete

The concrete is called **'green'** as soon as it is compacted in the framework until its solidification by setting. When the concrete turns solid, it is called **'young'** until it reaches a certain degree of strength permitting the removal of the form.

For the practical behaviour of concrete in service, its mechanical properties are decisive. Its **resistance to loading** is essential in the hardened stage. It is, however, insignificant in fresh concrete where the **workability** is of main concern.

Workability is not well defined and, therefore, not directly measurable, because it includes a certain number of fresh properties. As an example, two definitions of workability from the same country (USA) follow:

- WORKABILITY is that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed and compacted and finished. (ACI definition)
- WORKABILITY is that property of concrete which determines the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity. (ASTM definition)

Resistance to loading is the ability of the hardened concrete to bear the service load (dead and live load); (dead load = constant load in structures due to the mass of the members, the supported structure and permanent attachments or accessories; live load = any load that is not permanently applied to the structure).

Resistance to loading can be specified and measured exactly for different types of loads. Usually, it is expressed as strength.

2.4 Strength of concrete

Strength is defined as maximum resistance to load that a member or structure is capable to develop before failure occurs. It is measured with reference to the cross section of the structure member.

$$\text{Strength:} \quad \sigma = \frac{F}{A} \quad \left[\frac{N}{mm^2} \quad \text{or} \quad MPa\right]$$

where: F = applied load
A = cross section on which the load is applied

We distinguish different types of strength according to the type of load exerted:

Compressive, tensile, flexural splitting, shear, torsion adhesive, and impact strength.

The loading resistance of various structural members results from the combination of different types of strength, according to the actual stresses, and from concrete quality.

3. FRESH CONCRETE

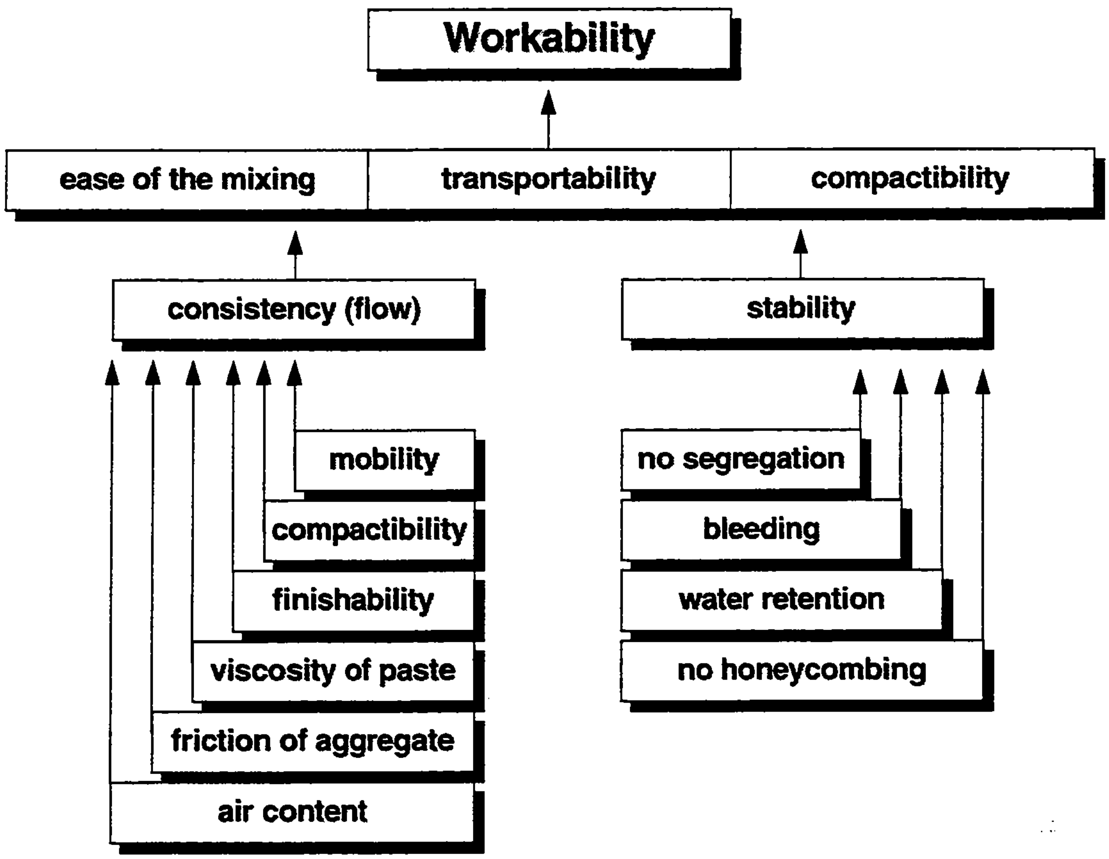
Fresh Concrete is the product that is obtained immediately after mixing the components.

3.1 Workability

The homogenized concrete mix, after it is taken from the mixer, must be suited to be transported to the destination point and to be placed into the moulds or formwork. The fresh concrete must completely fill the mould, even if the shape of the elements is very complicated and the interstices between the reinforcement are very small. A good compaction must be achieved and through all these steps the mix must remain homogeneous without segregation.

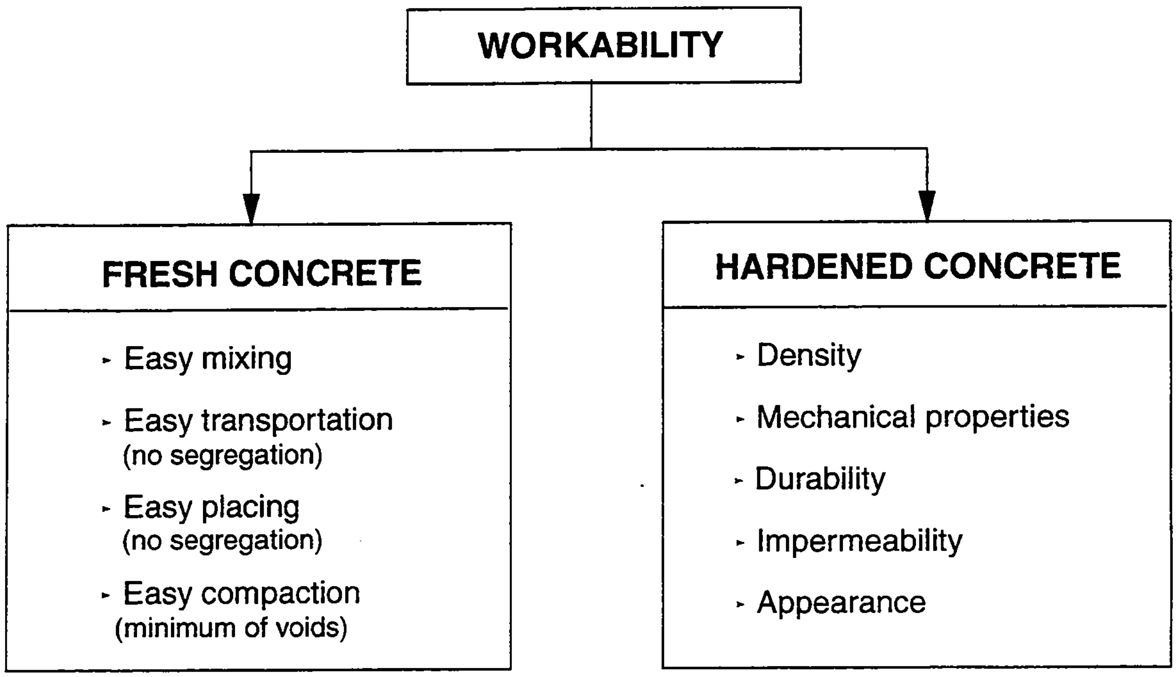
The ability of fresh concrete to meet all these requirements is called **workability** which includes a number of more or less defined properties (see following figure).

Fig. 2: Properties of fresh concrete related to workability



The workability influences not only all operations of placing and consolidating fresh concrete but also to a large extent, the quality of the hardened concrete. A dense concrete must contain a high amount of solid matter and very few voids filled with water, vapor or air. Very important concrete properties depend on the density.

Fig. 3: Effect of the workability on fresh and hardened concrete properties



The workability requirements vary from one country to another. They depend on the level of the building industry, on the quality requirements and on the quality of the available materials. Furthermore, tradition, economical and subjective factors influence the technical demands.

To characterize the workability of concrete mixes, the following terms are usually used in Central Europe:

Terms for workability:
very stiff
stiff
plastic
soft (wet)
flowing (liquid)

However, those terms are not clearly defined. In England for instance, completely different terms are used:

- Low, medium, and high consistency.

3.2 Influence on the Workability

The workability of concrete is influenced in various ways by its solid and liquid components and environmental conditions.

3.2.1 Effect of water

The workability is related to the water content that is available for the lubrication of a mix. By increasing the water content in the mix up to a certain limit, the workability of the mix can be improved, i.e. the mix will be more wet. If the water content exceeds a certain amount, there is the danger of segregation.

The water content of the mix is expressed in liters or kilograms of water per cubic meter of concrete (pound per cubic yard).

3.2.2 Effect of solid constituents

Solid matter (aggregate + cement) shows a double effect on the workability:

- The shape of the solid grains influences the mobility of concrete in the following manner:
  - Coarse particles impede the mobility by their angularity and friction;
  - The fine grains, on the other hand, improve it because they act almost like ball-bearings between the coarse grains. This action is distinctly noticeable when lime or fly ash are added to concrete: their spherical particles improve concrete consistency.
- By absorption of the surface, eventually also by chemical bond, part of the mixing water is fixed. Only the remaining 'mobile' part influences concrete consistency.

The effect of aggregate properties on workability is considerable.

> **Note:**
>
> Grain size distribution, angularity and surface texture of the aggregates significantly affect concrete consistency.
>
> The effect of cement properties on workability is very small

The effect must be attributed to the water requirement of cement which can be determined with standard methods on the cement paste. The chemical-mineralogical composition has a stronger influence on the water requirement than fineness and grain size distribution. Grain size distribution shows only little variation in industrial cements.

If the amount of cement added to a concrete mix is increased at a constant water content, a stiffening action is the result because more water is absorbed. If, however, both cement and water are increased, so that the w/c ratio remains unchanged, the lubricating action of the additional cement paste increases the fluidity.

Thus, the workability of a given aggregate mix can be improved in two ways: by increasing the water content only, or by increasing the dosage of both, water and cement. In the first case the quality of hardened concrete will be inferior; in the second case the quality is maintained but at higher costs.

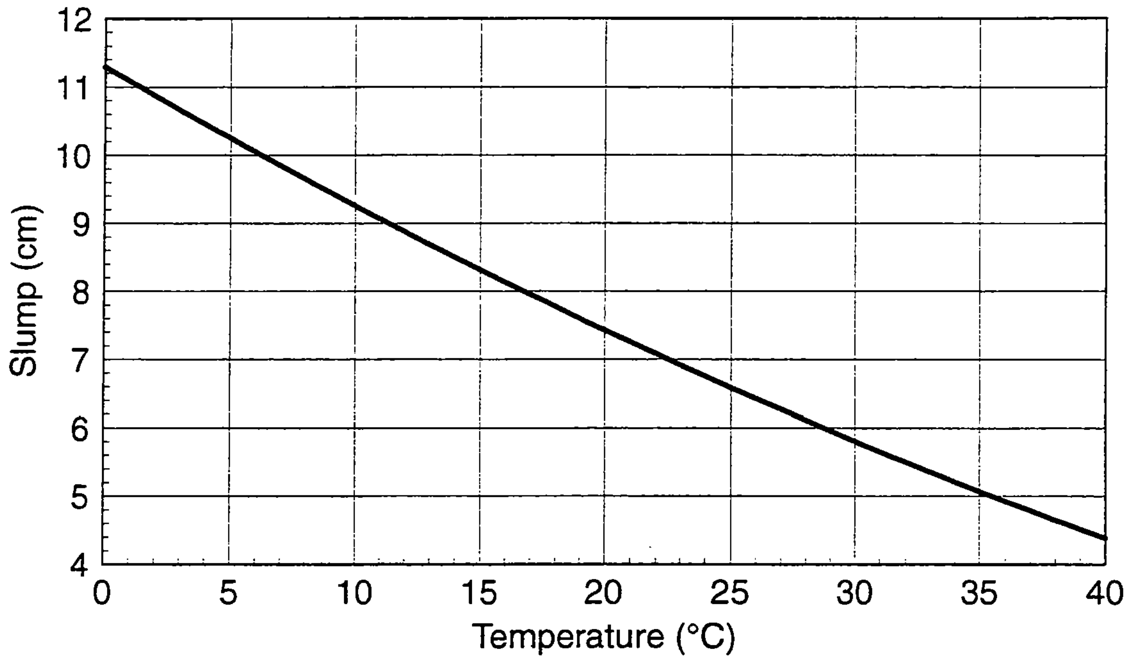
3.2.3 Effects of admixtures

Some admixtures such as plastifiers, water reducers and superplastifiers, can modify the concrete consistency even if added in small quantities (see chapter 'Concrete Main Components', paragraph 3.).

3.2.4 Effect of temperature

Increased temperature of the concrete and surrounding air contributes towards a stiffer consistency.

Fig. 4: Effect of temperature on the consistency (slump)



The consistency in the above mentioned figure was tested immediately after the mixing of the concretes according to the same mix design. Only the temperature of the materials (cement + aggregate + water) and the ambient temperature were changed.

3.3 Other properties of fresh concrete

3.3.1 Bulk density (unit weight)

The unit weight of fresh concrete gives some indication about the final void content which is responsible for final concrete properties. It is also a measure of the yield; i.e. it indicates the concrete volume produced with a specific amount of cement. The bulk density is determined by weighing a defined concrete volume. It depends very much on the water and less on the cement dosage. After compaction, the unit weight of ordinary concrete should be higher than 2300 kg/m^3.

3.3.2 Air content

Ordinary concrete which is well compacted, has an air content of about 0.5 to 1.5%. The measuring of the air content is important if entrained air is used. Air-entrained concrete is produced by using either an air-entrained cement or an air-entraining admixture during the mixing of concrete. Air-entrained concrete contains 3 to 7 Vol. % pores. - Entrained air improves the workability of fresh concrete.

3.4 From fresh to hardened concrete - Stages of development of concrete

'Green' and 'young' concrete are the terms for specific intermediary stages during the transition of concrete from a workable, more or less plastic mass, to an artificial stone.

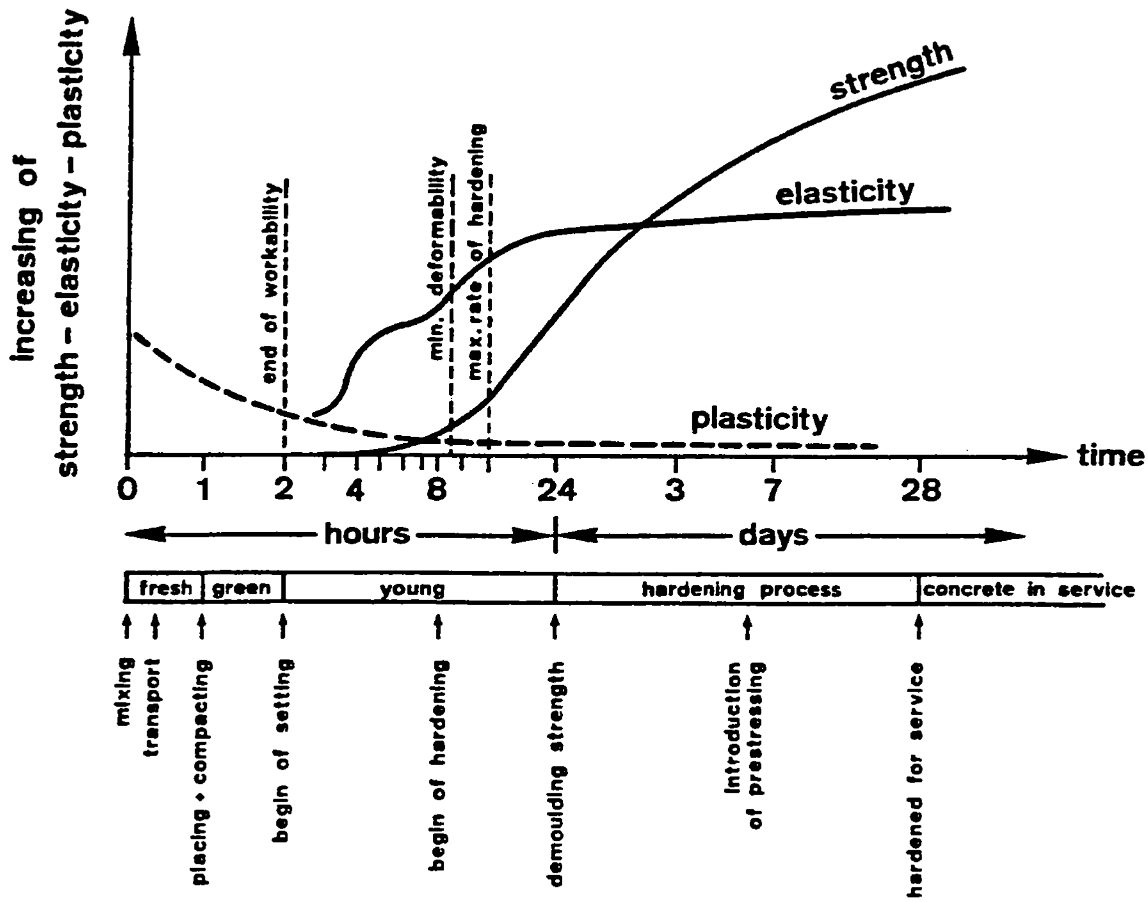
With the development of modern concrete technology and building methods, the properties of concrete at these intermediate stages have become important as well. The continuous development of hardened concrete is a sequence of periods of:

Concrete is a process:

Stiffening → Setting → Hardening

These periods are characterized by different growth rates of the various mechanical properties of the concrete (see following figure).

Fig. 5: Stages of development of concrete



Stiffening
of concrete is a change in the workability (sometimes also called slump loss) and begins immediately after mixing, sometimes even during mixing.

This can have unfavourable consequences if fresh concrete is not placed properly after mixing, or, especially if ready mix concrete is used, in precast manufacturing, or on large building sites and placing has to be delayed.

Concrete should be placed as soon as possible after mixing, but often there may be a time lapse of up to one hour or even more between mixing and placing. In these cases, too rapid stiffening can impede placing.

> The time during which concrete is still workable - at the right consistency - is very important for transporting and placing.
>
> This time depends on the purpose for which concrete is used and on the method of placing.

Setting
is the beginning of the hydration process and is indicated by the transition from the plastic to the solid state within a relatively short period of time.

The resistance against deformation during setting increases rapidly, strength less rapidly.

> **Note:**
>
> The time of setting of concrete is not identical with that of cement measured on paste according to standards.

The reason is that the setting of concrete is influenced not only by the setting behavior of the cement, but also by varying cement and water contents, by temperature and type of construction.

Until setting, deformations of concrete are almost totally irreversible; the elastic part of deformations becomes predominant only after setting.

Hardening
is the subsequent improvement of mechanical properties of concrete after setting. Soon after setting, the strength begins to increase more rapidly than the elasticity (Young-modulus). The rate of increase reaches its maximum between 5 and 20 hours after the addition of water.

3.5 Properties of 'Green' and 'Young' Concrete

Green concrete:

The mechanical properties of green concrete are important in practice, especially in the precast industry, where blocks, tubes and other concrete products are moulded by pressing. The moulded pieces have to be removed from the press as soon as possible in order to make room for the next series. However, this is only possible if the cohesion of the concrete is high enough, even before setting, to bear its own weight without deformation. Sometimes the moulded pieces (e.g. blocks) are stored in several layers. In this case, the strength after demoulding will have to be higher, so as to carry the whole load.

Young concrete:

Since young concrete at early age very often has to support a mechanical stress, it must have a minimum strength. Thus, the strength at this stage (after some hours) is decisive in the precast industry, where it determines the intervals at which precast elements can be demoulded, transported and piled up. It is also important in other building processes, for instance with prestressed concrete. The strength requirements vary according to the size and shape of the concrete element and the building method.

> **Early strength:**
>
> The compressive strength during the first few hours after placing is called early strength.
>
> It must reach approx. 10 to 20 MPa for demoulding in reinforced concrete and
>
> 35 MPa for the release of the prestressing wires in the pretensioned, prestressed concrete.

4. HARDENED CONCRETE

4.1 General

Hardened concrete is the final building material as it is obtained after stiffening, setting and hardening of fresh concrete. Hardening, however, continues for many years, slowing down after a certain strength has been reached. Therefore, it is generally accepted to consider the properties of hardened concrete at the age of 28 days as characteristic. They are commonly used for the design of concrete structures.

Hardened concrete must meet various requirements and maintain its properties during a very long time. Most important are the load-bearing properties and the durability of concrete.

The resistance to loading of concrete depends on its strength. But a building can never be loaded to the strength limit. Structural members are designed in such a way that the calculated stresses in concrete do not exceed certain permissible working values. According to the function of the building, other special requirements may be of importance.

A large variety of concrete properties can be obtained by the choice of the components and the mix design. However, the nature of concrete, the availability of the materials and economical considerations limit these possibilities.

4.2 Strength

According to the type and direction of load and stress, various types of strength react in concrete:

- **Compressive strength:**
  Compressive strength is the most important characteristic of hardened concrete. High compressive strength is, in most cases, accompanied also by an improvement of the other properties. compressive strength determinations show the best reproducibility. Therefore, compressive strength is considered as a general measure of concrete quality. The compressive strength of commonly used concrete after 28 days is in the range of 10 to 70 N/mm^2. The low values (~ 10 to 20 N/mm^2) are used for plain concrete, the medium values (~ 20 to 45 N/mm^2) for reinforced concrete and the high values (~ 50 to 70 N/mm^2) for prestressed concrete and precast elements.

- **Tensile strength:**
  Tensile strength is relatively low and amount to only approx. 1/10 of the compressive strength of hardened concrete. Because the tensile strength is low, it is practically not taken into consideration for structural design. Tensile stresses in the construction are carried by steel reinforcements.

- **Flexural strength**:
  It is difficult to determine the tensile strength of concrete and therefore bending or flexural strength is measured.

- **Impact strength;**
  Impact strength plays a significant role in special applications, e.g. for piles to be driven into the ground.

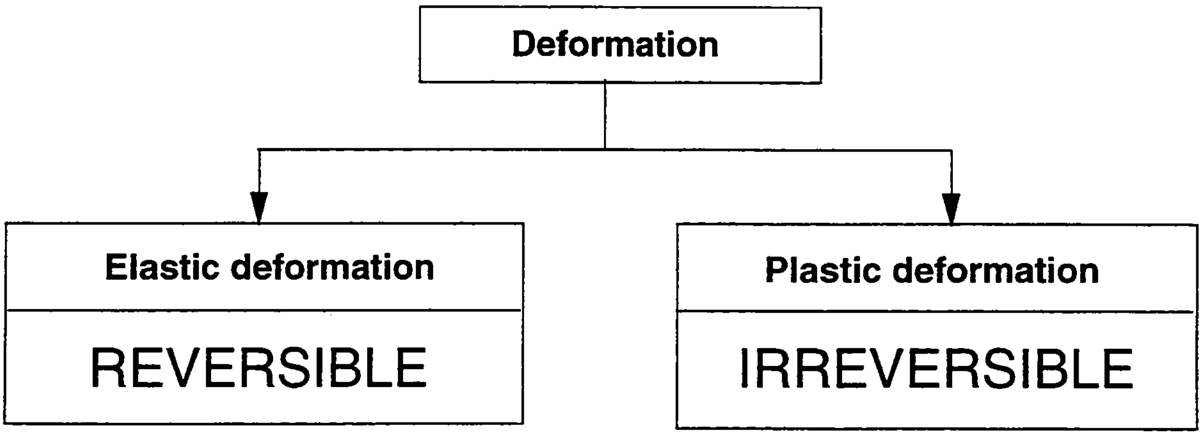
4.3 Deformation under load: modulus of elasticity and creep

Even momentary loads cause deformation of concrete. If they exceed certain limits, there is a risk of cracking.

> **Note:**
> Concrete is a plastic-elastic material

Its deformation is always composed of the two components: elastic and plastic.

The elastic deformation disappears when the load is removed, the plastic deformation remains.



In hardened concrete, the main part of deformation is elastic.

A quantitative measure of elasticity is the ratio between stress and corresponding strain. This ratio is termed **modulus of elasticity E** (Young modulus = initial tangent modulus).

$$E = \frac{\sigma}{\varepsilon}\ [GPa] \qquad \varepsilon = \frac{\Delta L}{L_0}\ [1]$$

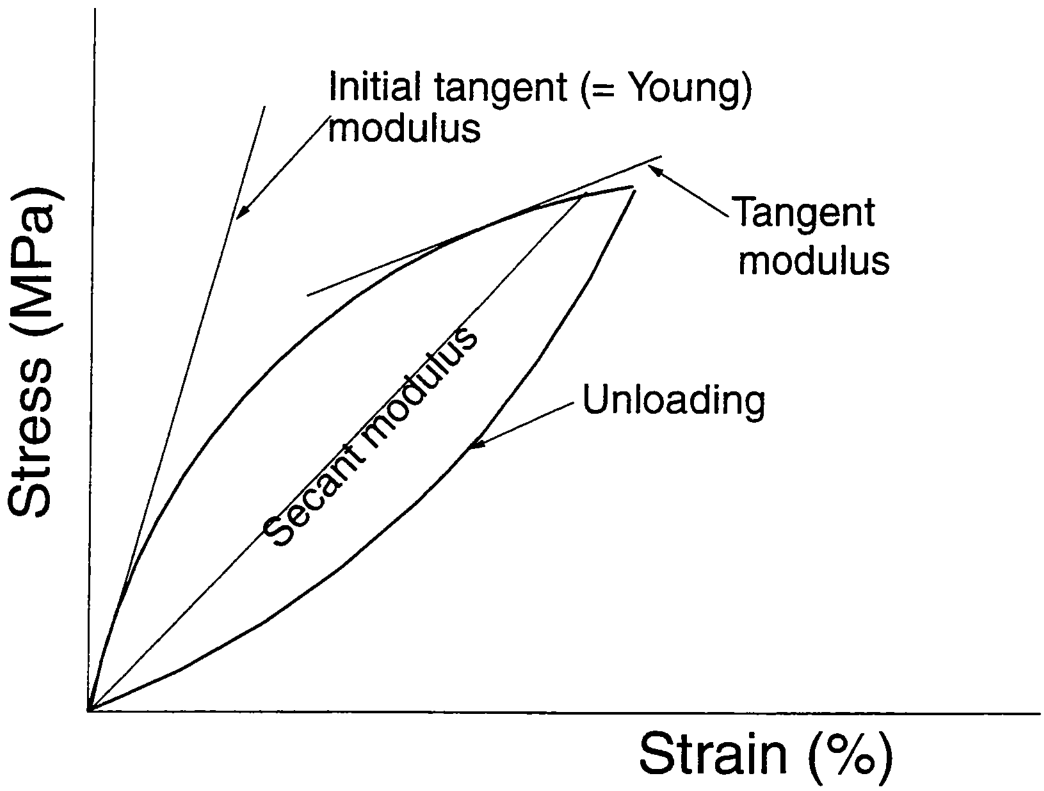
The modulus of elasticity may be measured in tension, compression or shear. The modulus in tension is usually equal to the modulus in compression and is frequently referred to as Young Modulus of elasticity (Table).

Table 1: Modulus of Elasticity of Different Building Materials

Material	Modulus of elasticity [GPa]
Steel	200 to 230
Aluminium	74
Copper	130
Natural stone	12 to 80
Concrete	20 to 50
Mortar	5 to 20
Timber	6 to 15

Due to the fact that concrete is neither ideally plastic nor ideally elastic material, the manner in which its modulus of elasticity is defined is somewhat arbitrary. Various forms of the modulus, which are used, are illustrated on the stress-strain curve in following diagram:

Fig. 6: Typical stress-strain curve for concrete



It also has to be distinguished between the 'dynamic E-modulus' and the 'static E-modulus'. The dynamic E-modulus is applied when concrete is exposed to oscillation. It can be calculated, for instance, from the rate of propagation of ultrasonic impulses and is a measure for the progression of deformation resistance. Using certain formulas, the compressive strength can be estimated from these results.

Creep:
Plastic deformation becomes more pronounced with longtime loading. The irreversible deformation by longtime loading is called creep.

> **Definition of plastic deformation:**
>
> The modulus of deformation is the ratio between the applied load and the irreversible deformation, expressed as function of time.

The creep is strongly influenced by the stress/strength ratio. With higher stress/strength ratio the creep increases. It also depends on other factors, such as temperature, humidity, etc. Creep attains approx. 1.5‰ per 1 MPa load during 1 year. Besides being a disadvantage, creep is also useful because it diminishes internal stresses. On the other hand, it reduces the effect of prestressing.

The deformability of concrete has certain limits:

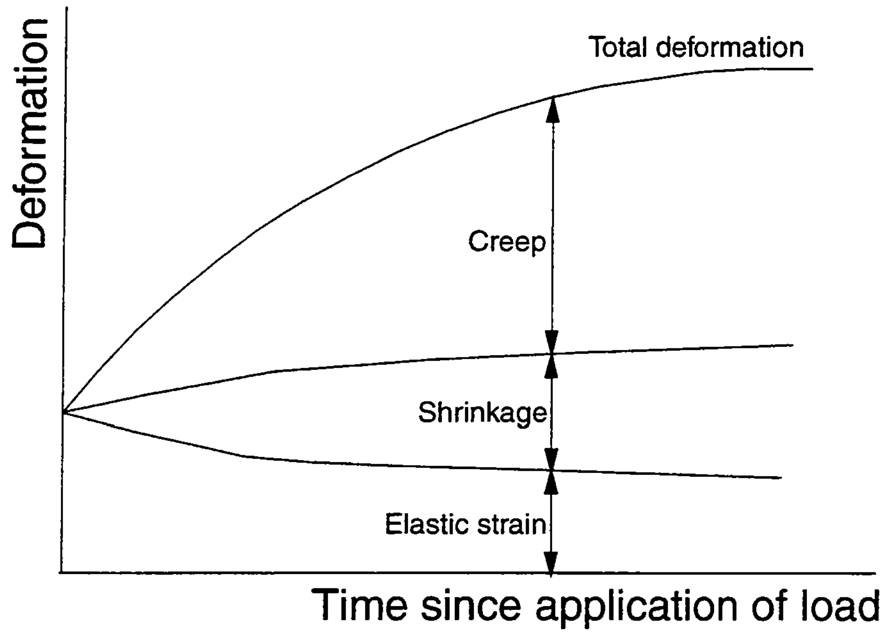
- If the stress grows beyond these limits, the concrete cracks or breaks.
- Strength and resistance against deformation dictate the limits:

- The higher the strength and the lower the resistance against deformation, the higher the limits of deformation.

$$\text{Deformation limit: } \varepsilon_{\lim} = \frac{\sigma_{\lim}}{E} \cdot 1000\,(‰)$$

Where: σ = strength, E = Young modulus

Fig. 7: Time-dependent deformations in concrete subjected to a sustained load



The deformability of hardened concrete is in the range of about 1‰. Another characteristic of the deformability is the ratio of the transverse strain to the longitudinal compression or of the transverse contraction to the longitudinal strain.

$$\text{Poisson's ration} = \frac{\varepsilon_{\text{transverse}}}{\varepsilon_{\text{longitudinal}}}$$

While the modulus of elasticity indicates only the alteration of size in one direction, the Poisson's ratio indicates to what extent the load modifies the shape and the volume of the concrete (compressibility). It decreases with time and is about 0.2 in hardened concrete.

Poisson's ratio and modulus of elasticity describe completely the deformation behavior of a material.

4.4 Density (weight of volume unit)

The dry density of the dry solid mass and the bulk density of the concrete have to be distinguished.

Density:

The density (specific gravity) - the weight per unit volume of a dry and pore-free substance (mass) - depends above all on the mix design as the density of cement (ρ = 3.0 to 3.15 g/cm^3), aggregate (ρ = 2.6 to 2.7 g/cm^3) and water ((ρ = 1.0 g/cm^3) vary little. The specific gravity of concrete is in the order of 2.3 to 2.5 g/cm^3.

Bulk density:

The bulk density (unit weight) - the weight of concrete per unit volume including voids - (about 2.2 to 2.4 t/m^3 for ordinary concrete) depends on the compaction of the concrete.

The ratio

$$\frac{\textit{Specific gravity} - \textit{Bulk density}}{\textit{Specific gravity}}$$

indicates the amount of voids in the bulk volume which are filled with water or air.

Voids weaken all mechanical properties of concrete and are, furthermore, decisive for the impermeability and thus the durability of concrete. Therefore, it is most important to compact the concrete as firmly as possible. Well compacted concrete contains not more than 1 to 2% voids of its volume.

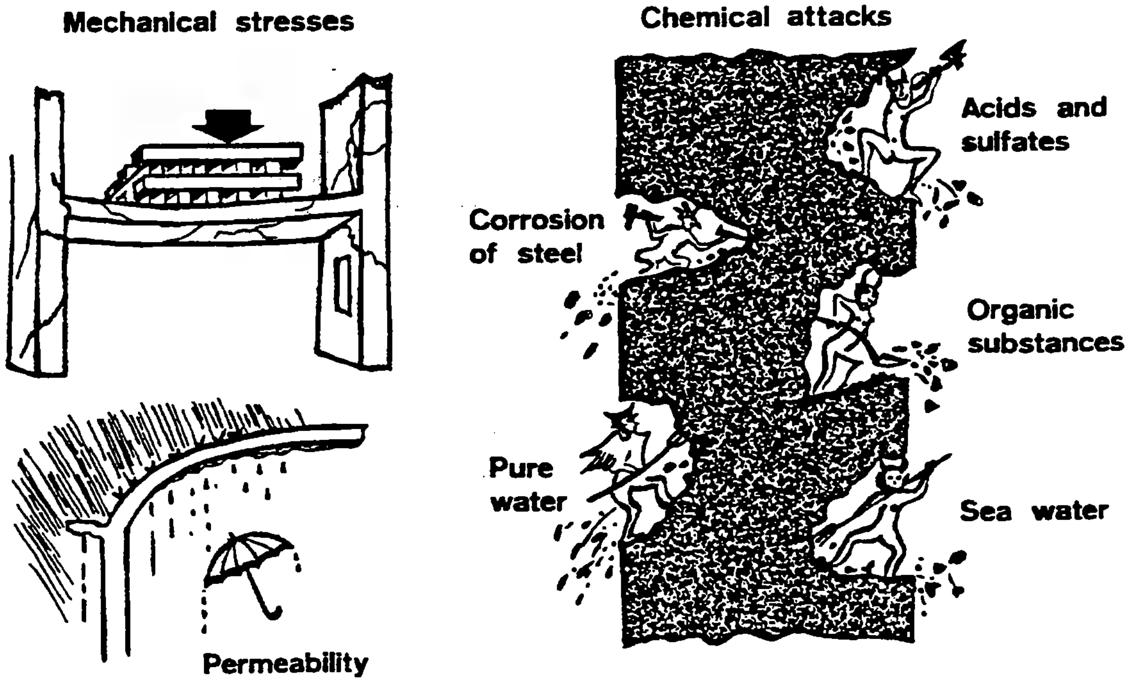
4.5 The durability of concrete

It is essential that concrete keeps its shape and size and does not suffer any deterioration of its substance which could also cause volume changes (soundness).

As was shown in previous chapters, the mechanical properties of concrete generally continue to improve with time. Concrete resists moisture and putrefaction as well as high temperatures (between 200 and 300°C). It does not burn. These are very important advantages that concrete has over other building materials.

In this paragraph, some factors influencing the durability are discussed.

Fig. 8: Durability of concrete



4.5.1 Volume changes

Concrete is always subject to changes of volume which can be detrimental if they exceed certain limits.

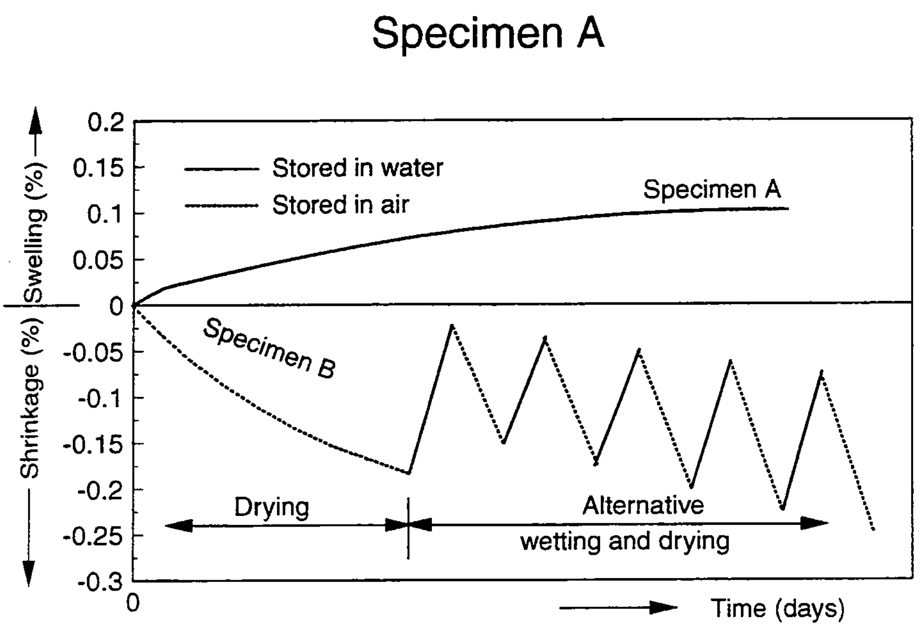
4.5.2 Volume changes due to physical stress

There are several types of stress which may cause volume changes:

- **Temperature Changes**
  Temperature changes cause expansion and contraction in concrete as in all other materials. These changes are in the same order of magnitude as in steel (approx. 10^{-5} for 1°C). If these volume changes are impeded, high stresses result, causing cracks. Changes due to the freezing - thawing cycle are very hazardous. At freezing temperatures, the water volume in concrete increases by about 9%. Due to this expansion and thermal stress, concrete can disrupt. The risk is heightened if de-icing agents (salts) are employed, because of additional complicated, detrimental effects. The best way to avoid this reaction is to created voids allowing the water to expand. This is done by enlarging pore volume by about 3 to 7 Vol.% with the aid of air-entraining agents (air-entrained concrete), (see chapter 'Concrete Main Components', paragraph 3.4).

- **Moisture Changes:**
  Moisture changes - desiccation or absorption of water in hardened concrete - cause shrinkage or swelling. These changes continue until an equilibrium of moisture with the surroundings is reached which usually takes several years. Maximum final shrinkage (determined as a change in length) of the hardened concrete is 0.2 to 0.65 mm/m, maximum swelling through storage in water at 20°C, 0.1 to 0.3 mm/m depending on atmospheric conditions.

Fig. 9: Moisture movements in concrete - swelling and shrinkage



Much higher and also more dangerous is shrinkage before the setting of concrete - plastic shrinkage. At intensive desiccation it can reach several per mill (‰). If a lot of water is allowed to evaporate during the critical period, namely when concrete has only low strength and is not prevented from shrinking, e.g. through reinforcement, plastic shrinkage-cracks may result.

To avoid the early shrinkage-cracks, concrete must be protected against desiccation. This can be achieved by covering the concrete with burlap or plastic sheets or by spraying it with water.

4.5.3 Volume changes due to alterations of the substance

Chemical alterations of a substance result in volume changes, causing stresses and possibly cracks.

In concrete mainly the cement stone or the reinforcement (corrosion) are attacked while aggregates are generally more resistant.

The volume of cement stone decreases during hydration because the volume of the hydration product is about 3 to 11% smaller than the original volume of cement and water. This chemical shrinkage has to be distinguished from drying shrinkage. Chemical shrinkage enlarges the gel pores and generally does not cause cracks.

A higher risk for concrete is the expansion of the cement stone caused by the reaction of free lime, periclase and sulfate. These compositions produce unsoundness.

Subsequent reactions between cement and reactive aggregates in hardened concrete can have a deteriorating effect on concrete, especially if alkalis in the cement react with reactive silica in the aggregates.

From the external chemical attacks the most important reactions are those with CO_2 in the air, with acids, sulfates and ammonium salts.

Table 2 shows the most important detrimental influences.

Table 2a: Effect on Concrete by Various Chemical Agents: ACIDS

Acid type	Effect on Concrete
Acetic	Disintegrates slowly
Acid waters	Natural acid waters may erode surface mortar, but usually action then stops
Carbolic	Disintegrates slowly
Humic	Depends on humus material, but may cause slow disintegration
Hydrochloride	Disintegrates
Hydrofluoric	Disintegrates
Lactic	Disintegrates slowly
Muriatic	Disintegrates
Oxalic	None
Phosphoric	Attacks surface slowly
Sulfuric	Disintegrates
Sulfurous	Disintegrates
Tannic	Disintegrates slowly

Table 2b: Effect on Concrete by Various Chemical Agents: SALTS and ALKALIES

Salts and Alkalies (solution)	**Effect on concrete**
Carbonates of - Ammonia - Potassium - Sodium	None
Chlorides of - Calcium - Potassium - Sodium - Strontium	None unless concrete is alternately wet and dry with the solution
Chlorides of - Ammonia - Copper - Iron - Magnesium - Mercury - Zinc	Disintegrates slowly
Fluorides	None except ammonium fluoride
Hydroxides of - Ammonia - Calcium - Potassium - Sodium	None
Nitrates of Ammonium	Disintegrates
Nitrates of - Calcium - Potassium - Sodium	None
Potassium permanganate	None
Silicates	None
Sulfates of Ammonia	Disintegrates
Sulfates of - Aluminium - Calcium - Cobalt - Copper - Iron - Manganese - Nickel - Potassium - Sodium - Zinc	Disintegrates; however, concrete products cured in high pressure steam are highly resistant to sulfates

Table 2c: Effect on Concrete by Various Chemical Agents: PETROLEUM and OILS

Petroleum	Effect on concrete
Heavy oils[t] - below 35 deg Baume	None
Light oils[t] - above 35 deg Baume	None - Require impervious concrete to prevent loss from penetration, and surface treatments are generally used
Benzine Gasoline Kerosene Naphtha High octane gasoline	None - Require impervious concrete to prevent loss from penetration, and surface treatments are generally used.

Table 2d: Effect on Concrete by Various Chemical Agents: COAL TAR SESTILLATES

Tar derivatives	Effect on concrete
Alizarin Anthracene Benzol Cumol	None

Steel reinforcement corrodes when it is attacked by moisture or acids. This not only diminishes the strength of the steel bars, but also damages the concrete due to an increase in volume of the corrosion products. Well compacted concrete, as an alkaline medium with pH-values above 9.5, protects steel against corrosion.

Impermeability (or low permeability) of concrete to water, other liquids and gases is very important for the protection of the steel reinforcement as well as for some concrete structures. In most cases, a well compacted concrete has a sufficient impermeability.

To protect concrete against specific attacks of aggressive water, chemicals and gases, a special surface treatment with chemically resistant coating is necessary. In some cases, a special concrete with special cements or of a special composition is required.

Table 3: How can we improve the durability of concrete?

⇩	⇩
Low water/cement ratio Special cements High cement content Maximum compaction	Air-entrainment Blended cements ⇩ Surface treatment
⇩	⇩
Effective curing (Autoclave curing)	Suitable aggregates
⇩	⇩
Dry concrete	Prestressing
⇩	
Impermeable concrete	

Table 4: How can we improve the impermeability of concrete?

⇩	⇩
Waterproof membrane ⇩ Watertight aggregates and joints	Plastic, workable mix with low water/cement ratio Increased cement content Air-entrainment
⇩	⇩
No cracks and segregation Uniformity ⇩ Expansive cement	Thorough mixing Proper placing Reduced water at top lifts ⇩ Effective curing
⇩	⇩
Prestressing	Surface treatment

4.6 Thermal properties

- **Thermal conductivity**
  Thermal conductivity is the ability of hardened concrete to transmit heat. It is usually measured in W/mK or kcal/mh°C. For ordinary concrete the values lie within the range of 1.30 to 2.10 W/mK (1.10 to 1.80 kcal/mh°C).

- **Specific heat**
  Specific heat is the measure of heat capacity and is defined as the amount of heat necessary to change the temperature of 1 kg concrete by 1°C. It varies between 0.84 to 1.17 kJ/kgK (0.20 to 0.28 kcal/kg°C).

- **Coefficient of thermal expansion**
  Coefficient of thermal expansion indicates either a change in volume, or usually a change in length in relation to temperature changes. The very similar coefficient of thermal expansion of concrete and steel is one of the reasons for practical utilization of steel as reinforcement in concrete. Standards and building codes of most countries prescribe the same value for steel and concrete (10^{-5}/°C).

Resistance to high temperature
Concrete, if properly designed, placed and cured, performs remarkably well with regard to

fire, heat and blast resistance ('Concrete does not burn').
Temperatures below 250°C scarcely affect the concrete strength, but is subjected to about 300°C, there are marked signs of strength loss (Table 4a). The strength loss is considerably lower, if the aggregate does not contain silica, but is composed e.g. of limestone, basic igneous rock, and particularly of crushed brick and blast furnace slag. Low conductivity of concrete (lightweight concrete) as well as special cement (high-alumina) improves the fire resistance.

Table 5: Loss of compressive strength of ordinary concrete under continuous expoure to high temperatures

Temperature (°C)	<150	250 to 320	430 to 500	600 to 650	>820
Reduction in compressive strength (%)	negligible	15-25	40-50	75-85	disinte-grated

4.7 Aesthetic properties

In constructions where it is intentionally left exposed (without stucco), concrete should be appealing to the eye, i.e. color and texture should be decorative.

4.8 Acoustic properties

Sound protection is an important factor in many types of buildings due to their design. The concrete as a relatively heavy material (ρ = 2.2 to 2.4 g/cm^3) has generally favorable acoustic properties.

Generally it can be distinguished between:

- Sound insulation (sound conductivity) and
- Sound absorption.

Sound insulation:
For sound insulation two types of measurements and technical values are important for the building design:

- Sound transmission loss (STL) is defined as the number of decibels (dB) by which the level of airborne sound intensity is decreased when transmitted within the structure. STL of concrete walls and slabs is directly proportional to their thickness.
- Sound impact loss: the impact noise (i.e. by footsteps on the floor, appliances mounted on the wall) and their level at different distances from the origin is measured. The values are expressed also in dB.

Sound absorption:
The coefficient of sound absorption indicates the difference between the reverberation time and frequency of an empty standardized room and the same room after it has been furnished with a certain amount of absorptive material.

5. FACTORS INFLUENCING THE STRENGTH OF CONCRETE

The concrete properties are the result of a combination of many factors. Some can be attributed to the material itself, but just as important are the external influences. As has been mentioned previously, the most important and most characteristic property of concrete is its

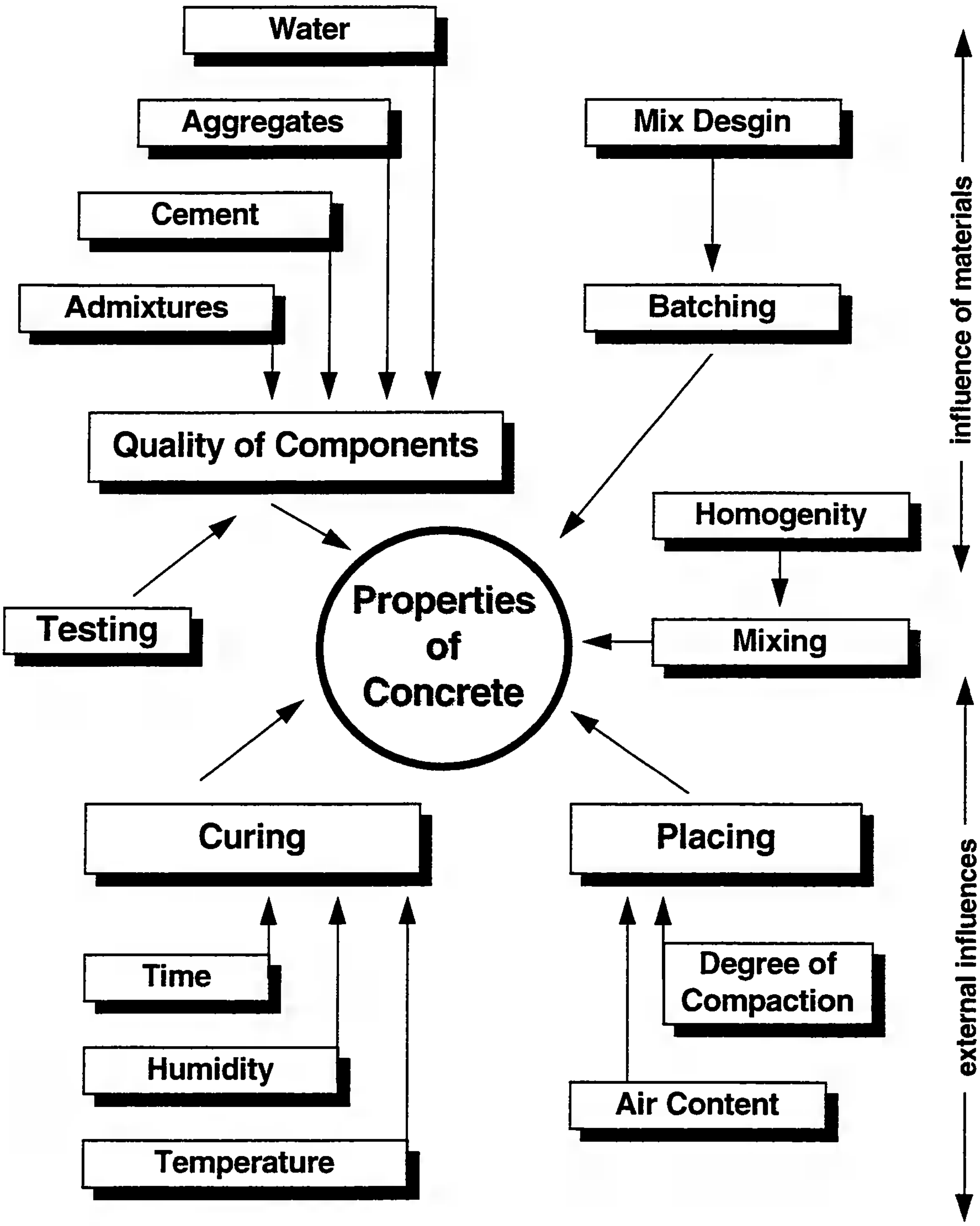
compressive strength after 28 days which can also serve as an indication for other properties. Therefore, this paragraph will be mainly concerned with concrete strength.

The main factors influencing the strength are (see also Fig. 10):

Strength influencing factors:

- Properties of the constituents
- Mix proportions (mix design, formula)
- Way of handling fresh concrete
- Conditions under which the concrete hardens

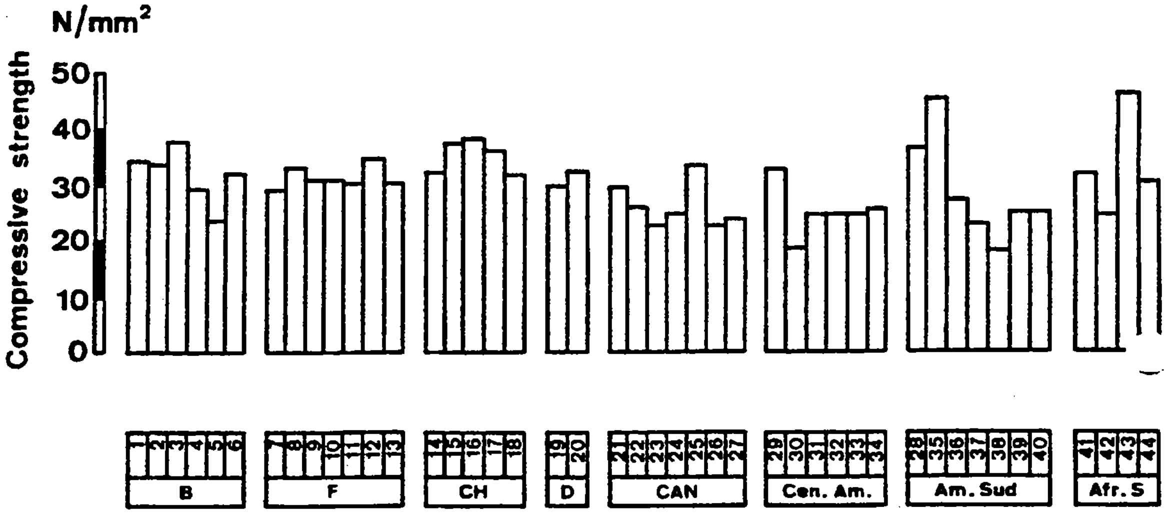
Fig. 10: Factors influencing the strength of concrete



One and the same concrete may show various values when tested with different methods. Thus, the method of testing can influence the test results but not the actual properties of concrete.

The following figure gives an indication of the range in which strength values can vary; it shows the results of tests carried out on specimens of the most common cements produced in ready-mix plants which are affiliated with "HOLDERBANK".

Fig. 11: Compressive strength after 28 days of samples of 44 Ready-Mix Plants



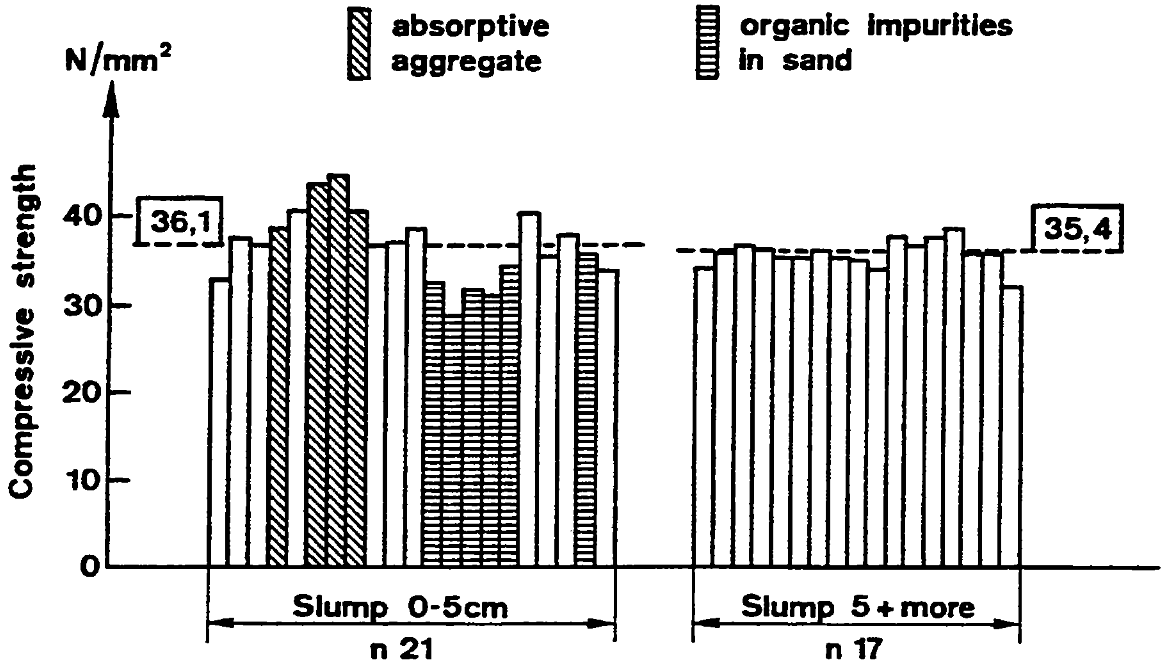
5.1 Influence of the constituents

5.1.1 Aggregates

Aggregates represent the largest part of concrete in volume (60 to 75%) as well as in weight. Compressive strength of natural aggregates in normal weight concrete exceeds 2 to 3 times the strength of cement stone. Thus, it is the strength of the cement stone or the bond that limits the concrete strength, the cement stone being the weaker constituent.

Aggregates of various origin - if they are clean and free of deleterious substances - develop practically equal concrete strength if used with the same cement and mix formula (see following figure).

Fig. 12: Effect of aggregate on compressive strength concrete with 350 kg/m³ cement and w/c ratio of 0.55



> **Note:**
>
> The strength of aggregates does not have a influence on the compressive strength of ordinary concrete if they meet basic quality requirements.

The concrete made of various aggregates with equal strength show very different consistencies This is obviously due to the grading, angularity and surface roughness of the aggregates, requiring various amounts of water to obtain concretes of the same workability. The water requirement is mostly influenced by the amount and properties of sand (fine aggregates). Grading, the maximum size and shape of the aggregates determine the volume of voids in a compacted aggregate mix as well. The percentage of void volume (varying between 20 to 40%) indicates the volume of cement paste (cement plus water) required to obtain a good concrete mix.

> **Note:**
>
> Grading and shape of the aggregates determine the required amount of water and cement and thus strongly influence the strength of concretes of equal consistency.

Other properties of aggregates such as: porosity, unsoundness or lack of chemical resistance affect the concrete durability.

5.1.2 Water

Water represents the second largest portion of the volume of fresh concrete. The quality of water only exerts influence on concrete strength if it contains deleterious impurities.

The required water content of a concrete mix depends on the other constituents (cement, aggregate, admixture).

5.1.3 Cement

Cement has a primary and direct effect on concrete strength by its material properties:

Composition ↘			↗	Water requirement
	= Cement properties		→	Stiffening and hardening
Fineness ↗			↘	Final strength

The water requirement of cement measured on paste of normal consistency has only little influence on the water requirement of concrete (Fig. 13), much less than the aggregate.

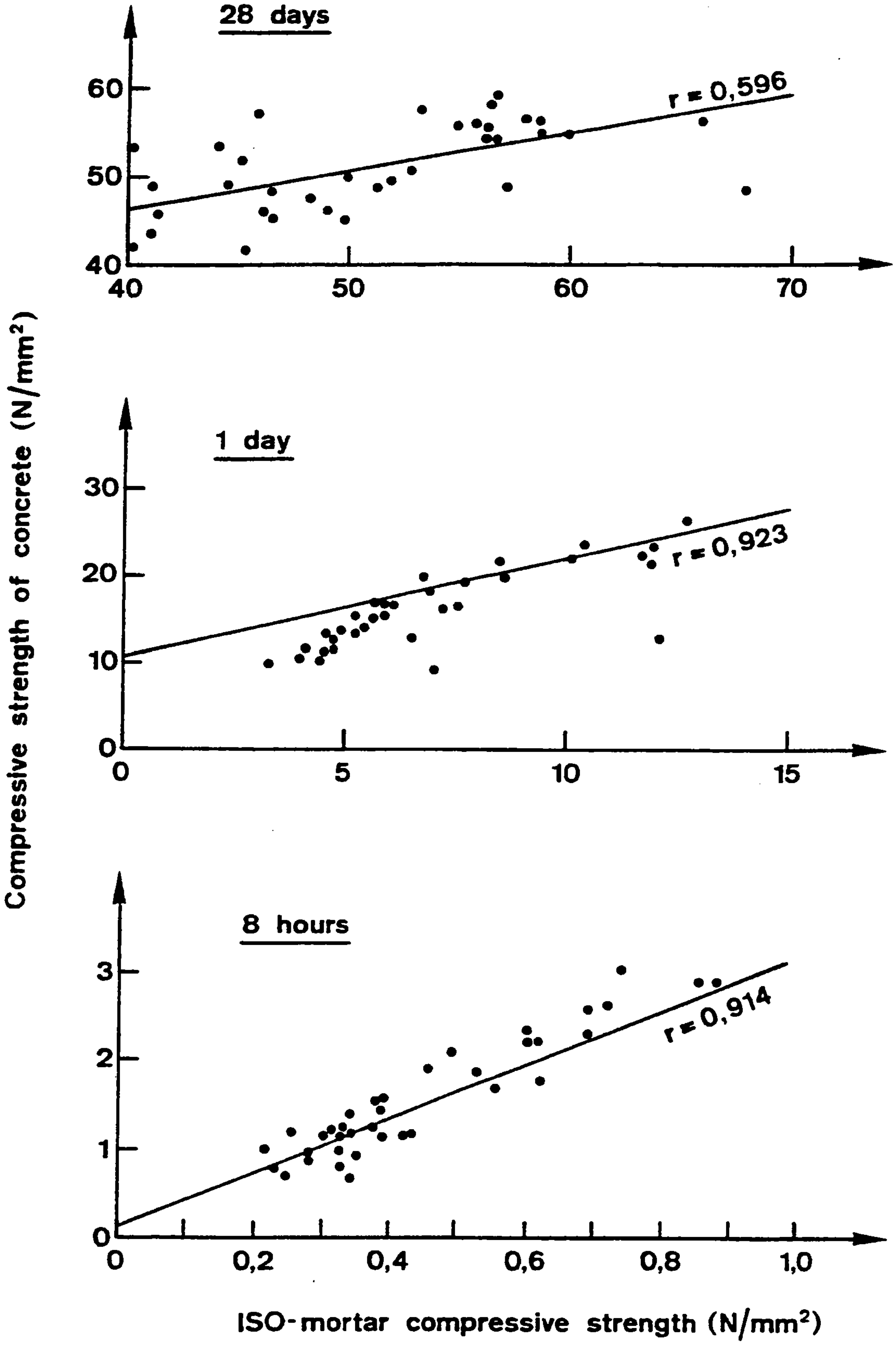
Table 6: Water requirement of standard cement paste and concretes of different Consistency

Consistency	OPC Cement A		OPC Cement B		OPC Cement C	
	Water Requirement (%)	Vebe Consistency (sec)	Water Requirement (%)	Vebe Consistency (sec)	Water Requirement (%)	Vebe Consistency (sec)
Ref.: Standard cement paste	*24*	–	*29*	–	*29.75*	–
Concrete: stiff	52	14.8	53.5	15.0		
Stiff-plastic	53.5	10.0			55	10.5
Plastic	55	5.0	57.5	4.5	58	5.6

Concluding from the strength test results on standard cement mortar, only a rough estimate of the concrete strength can be made.

With increasing standard mortar strength, concrete strength (with the same formula and aggregate mix) generally tends to increase slightly, especially after 28 days (see diagram below). The correlation between strength of concrete and mortar is poor; the ratio of both varies strongly with each individual cement. Cements with higher mortar strength can have even lower concrete strength.

Fig. 13: Relation between concrete and standard mortar strength (determined in Concrete Laboratory of the TC-MD on 37 OPC)



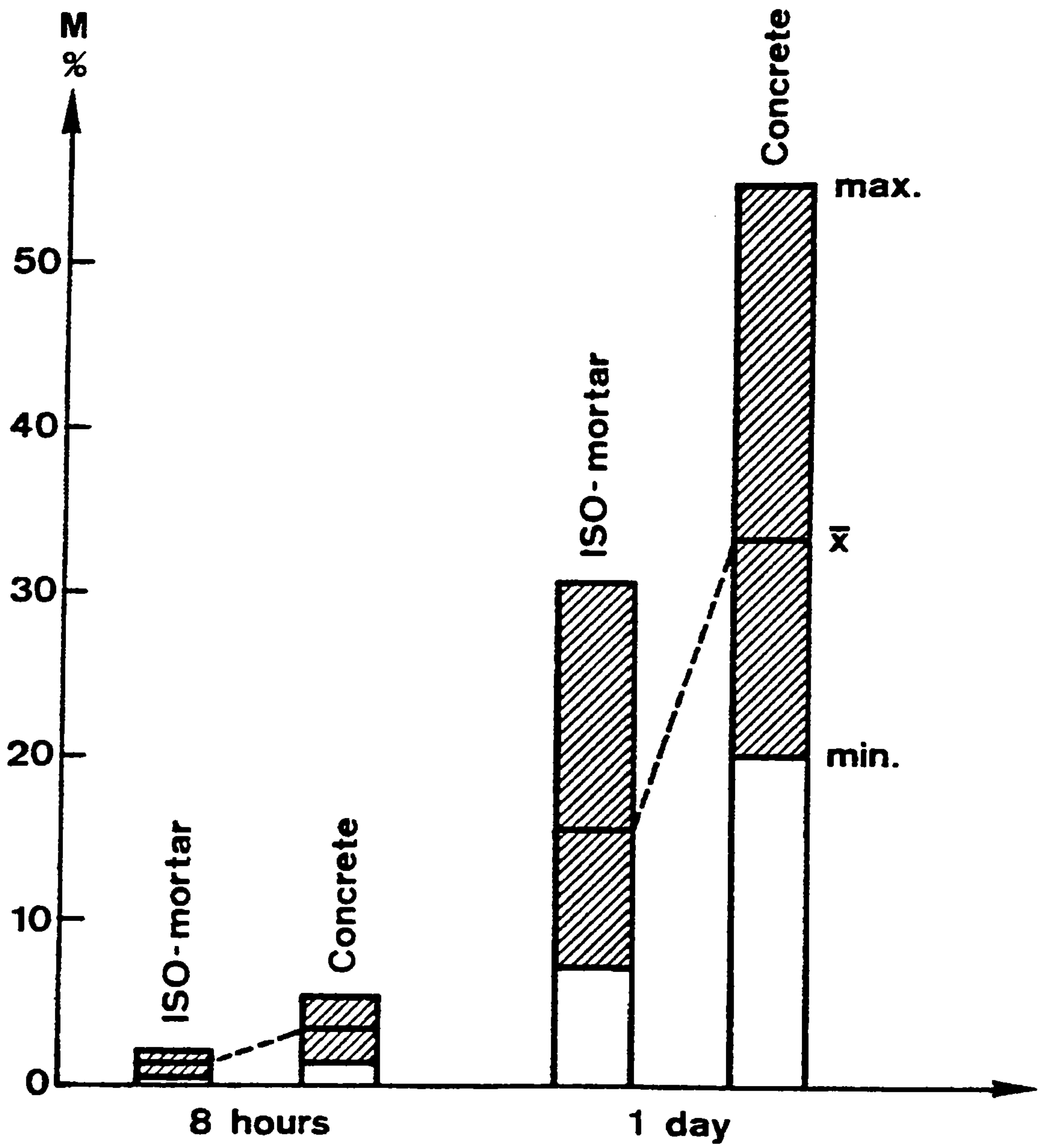
Note:

It is not possible to deduce from the standard mortar strength of various cements the strength of concretes of equal composition.

Important statement:

The ***hardening rate*** of concrete is much faster than that of standard mortar, as can be seen in the following figure. This is of utmost practical importance because on the job site under normal conditions (t = 15 to 25°C) the concrete reaches a certain percentage of its final strength much sooner than standard mortar.

Fig. 14: Maturity Percentage of Mortar and Concrete



(Tested on 37 OPC from the «Holderbank» Group plants)

Due too different rates of hardening, the effect of cement properties on early strength is much stronger than on final strength. Finer grinding results in only slightly higher final strength but considerably higher early strength. With different cement compositions (above all blended cements) a concrete showing lower initial strength may have the same or even higher final strength than a concrete with higher initial strength. For more information regarding the influence of the cement properties, see paper **'Cement'**.

The influence of admixtures has already been described in paper **'Concrete Main Components'**.

5.2 Influence of mix proportions

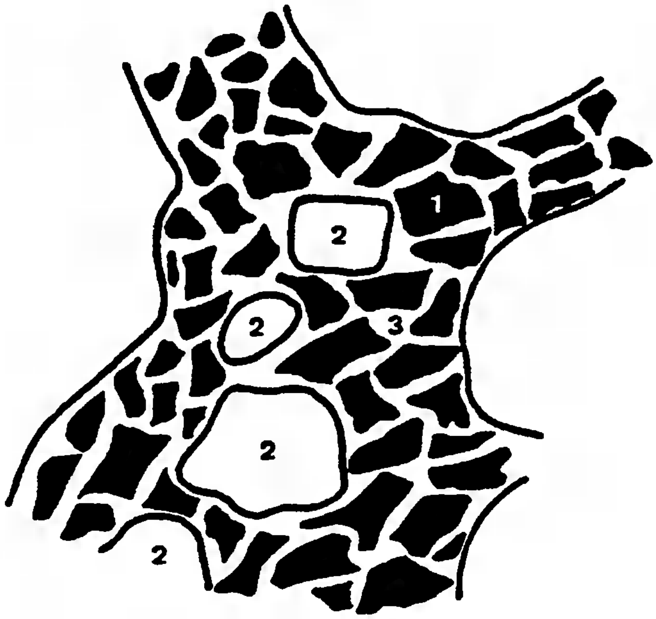
5.2.1 Water / Cement ratio

As already mentioned, the concrete strength depends essentially on the strength of the cement stone, and is only partially determined by the cement strength as measured on standard mortar. There must be other factors as well. The strength of mortar made with a given cement depends on its compaction, i.e. on the part of volume occupied by solid material and by voids (gel pores and capillaries).

The water requirement of cement for complete hydration is about 25%; another 15% is contained in the gel pores. If concrete contains less than 40% water, cement does not hydrate completely. Furthermore, since an extremely dry concrete cannot be compacted adequately, a deficiency of water causes inferior strength. For reasons regarding the workability, however, the concrete usually contains more water than the cement requires.

The following figure shows how the compaction of mortar depends on the ratio of the water content to the cement content:

Figure 15: Structure of fresh cement mortar



Water/Cement ratio 0,5

Water/Cement ratio 0,7

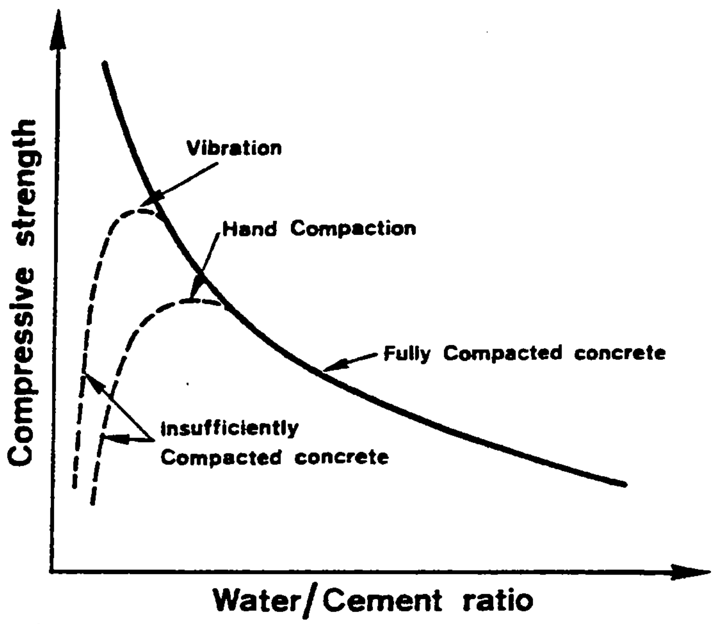
1 Cement grain

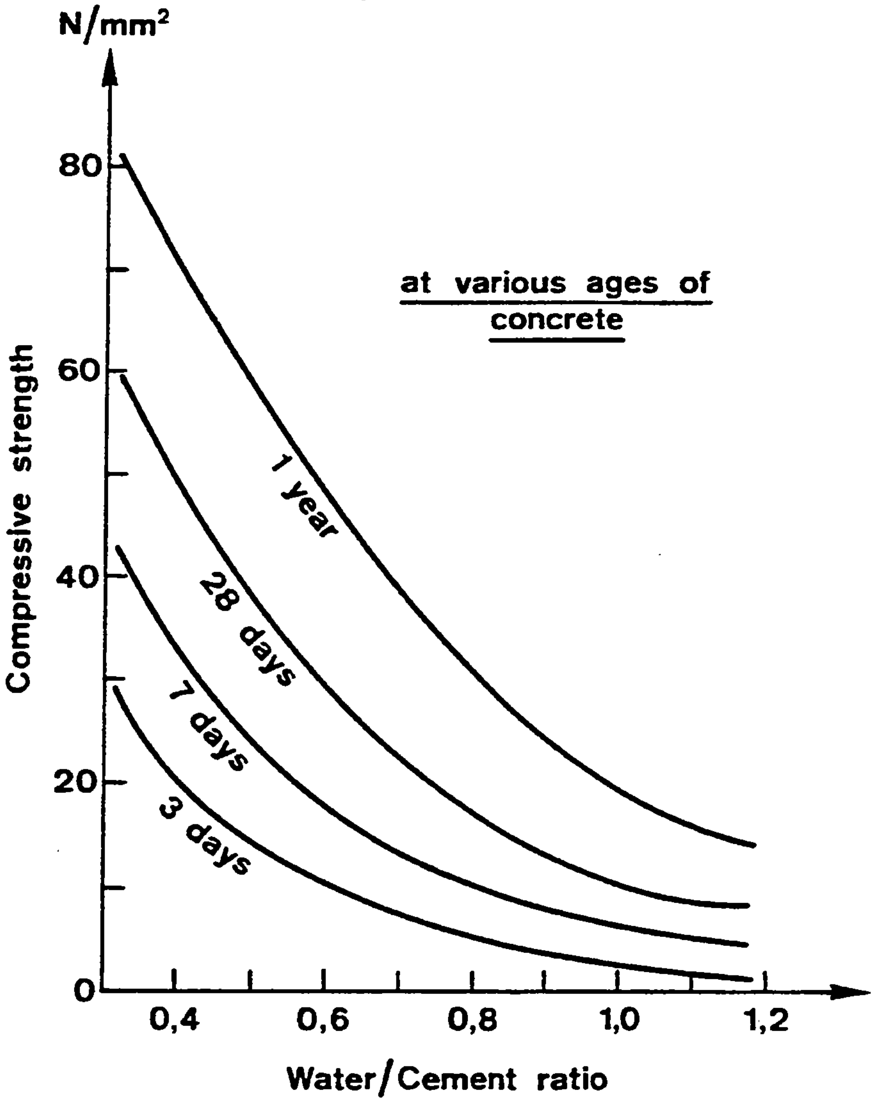
2 Sand grain

3 Water and Air

This weight proportion is usually termed **water/cement ratio (w/c ratio)**. While standard mortar has always the same prescribed w/c ratio, the water content of concrete varies according to the desired consistency and the water requirement of the aggregate and of the cement to obtain this consistency. The next two diagrams show the effect of the w/c ratio on the concrete strength.

Fig. 16: Relation between compressive strength and water/cement ratio of concrete



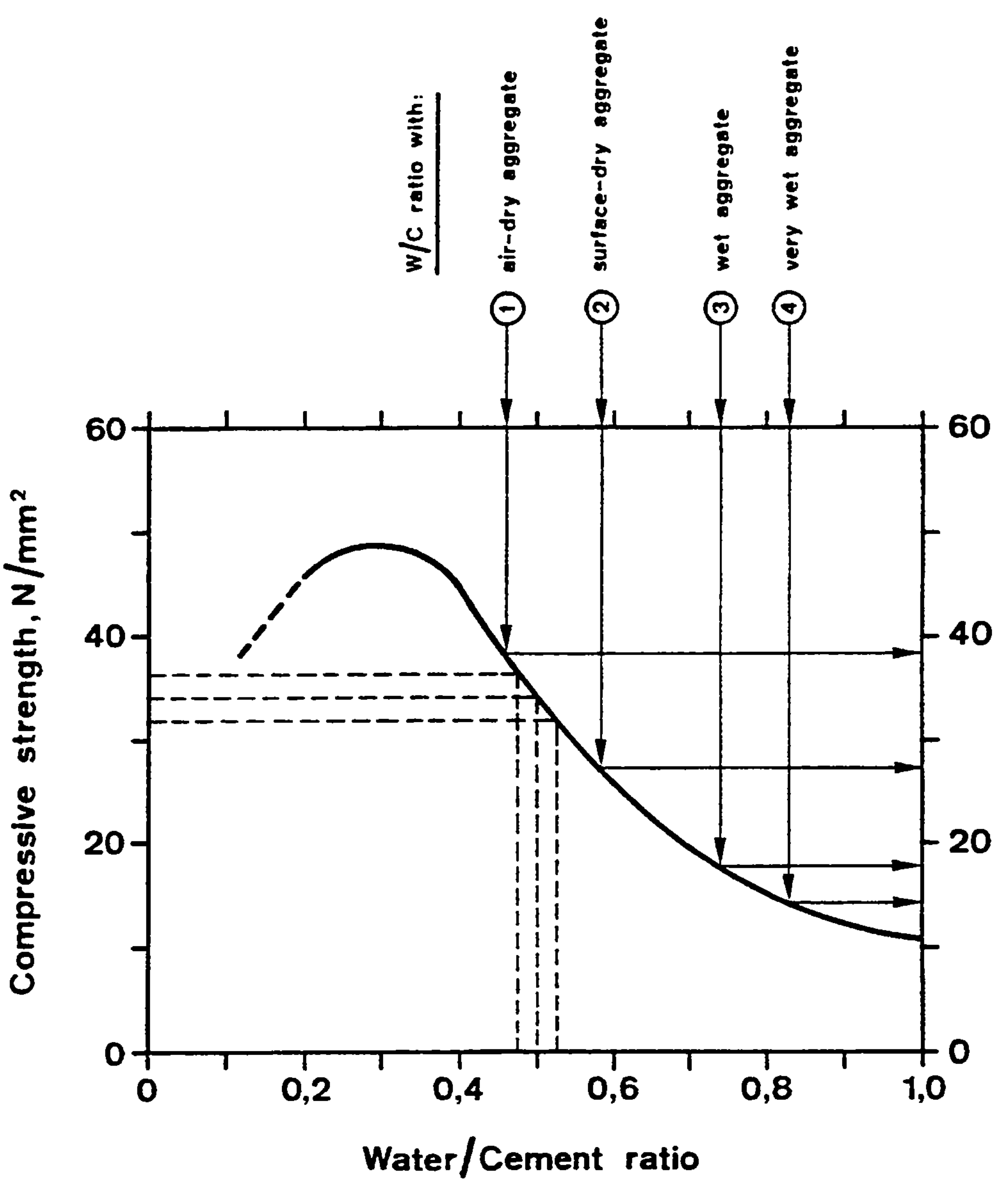


> **Important statement:**
>
> For the best concrete quality it is important to choose the lowest possible w/c ratio that still enables the concrete to be perfectly compacted.

In the concrete standards of different countries the maximum permissible w/c ratio for different types of structure is fixed (see tables later: Requirements for concrete acc. to DIN).

One of the most common causes of poor quality of concrete is the addition of too much water. Following figure shows how an inaccurate measurement of the quantity of mixing water or an uneven moisture content of aggregates may impair the strength of concrete. The moisture content of the aggregates must be deduced from the amount of water to be added.

Fig. 17: Influence of change in water content on compressive strength



Bolomey's Equitation

Various formula have been proposed to predict concrete strength on the basis of mortar strength and w/c ratio e.g. by Féret, Abrams, Bolomey, etc. The formula which is the simplest and most frequently applied, is the Bolomey's equation considering the reciprocal value of the w/c ratio, the cement/water ratio:

Bolomey's Equation:

$$\boxed{\chi_{concrete} = \chi_{cement} \cdot \left(\frac{c}{w} - 0.5 \right) + b}$$

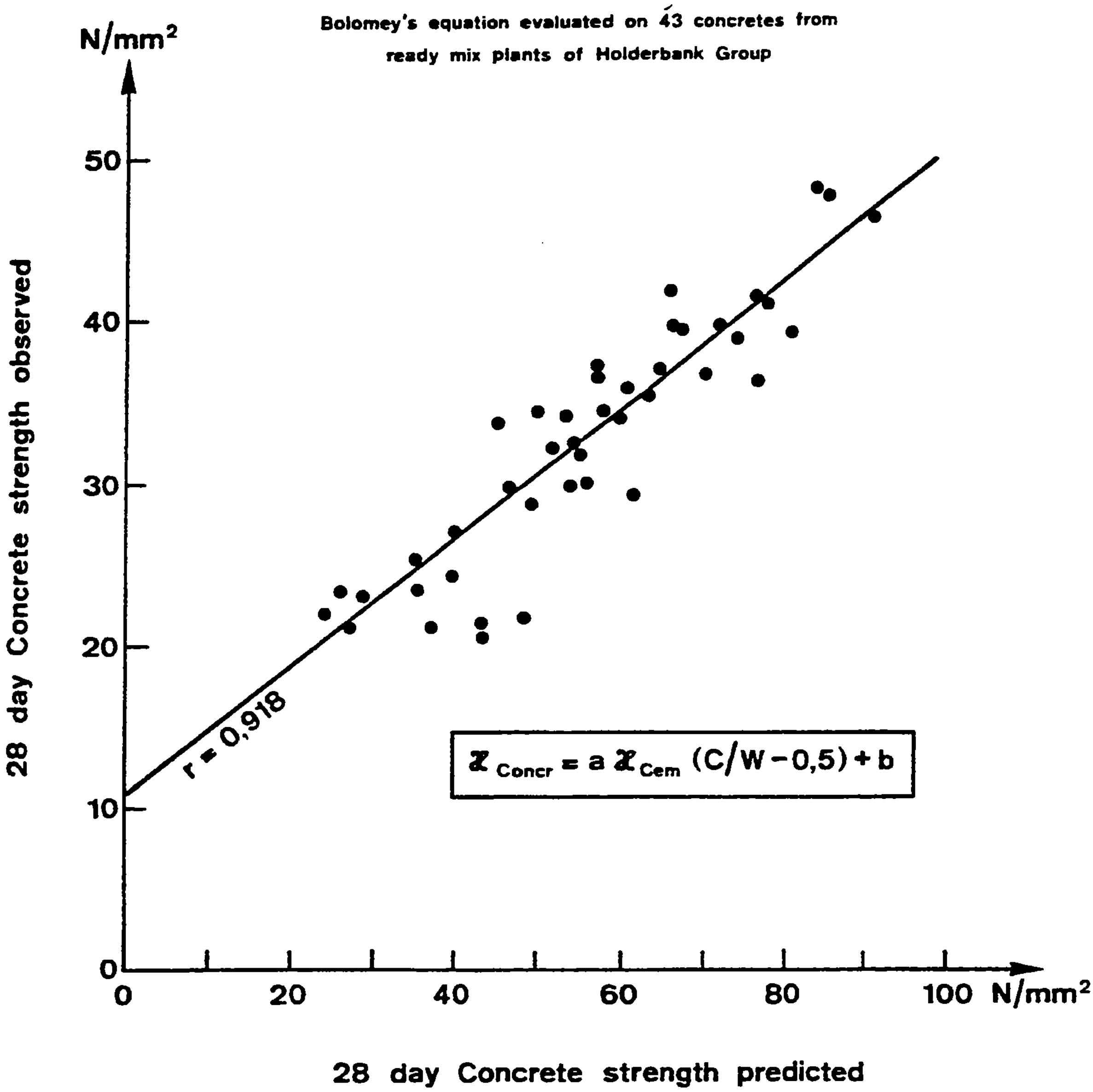
where: $\chi_{concrete}$ = (predicted) concrete strength

χ_{cement} = (observed) mortar strength

a, b = constants depending on the mortar and concrete testing method, age and curing specimen, aggregate quality; cement content and cement characteristics not included in the χ_{cement} etc.

Based on the coefficient of correlation of 0.918 it can be assumed that effects other than the cement/water ratio and mortar strength have a negligible influence on the 28 day concrete strength (see following figure). To predict the early strength, the equation is less suitable since the relation between mortar and concrete strength is influenced also by the faster hardening rate of concrete in comparison to mortar.

Fig. 18: Relation between calculated and observed concrete strength



The calculated concrete strength is only obtained, however, if the concrete is perfectly compacted (porosity < 1%).

5.2.2 Cement content

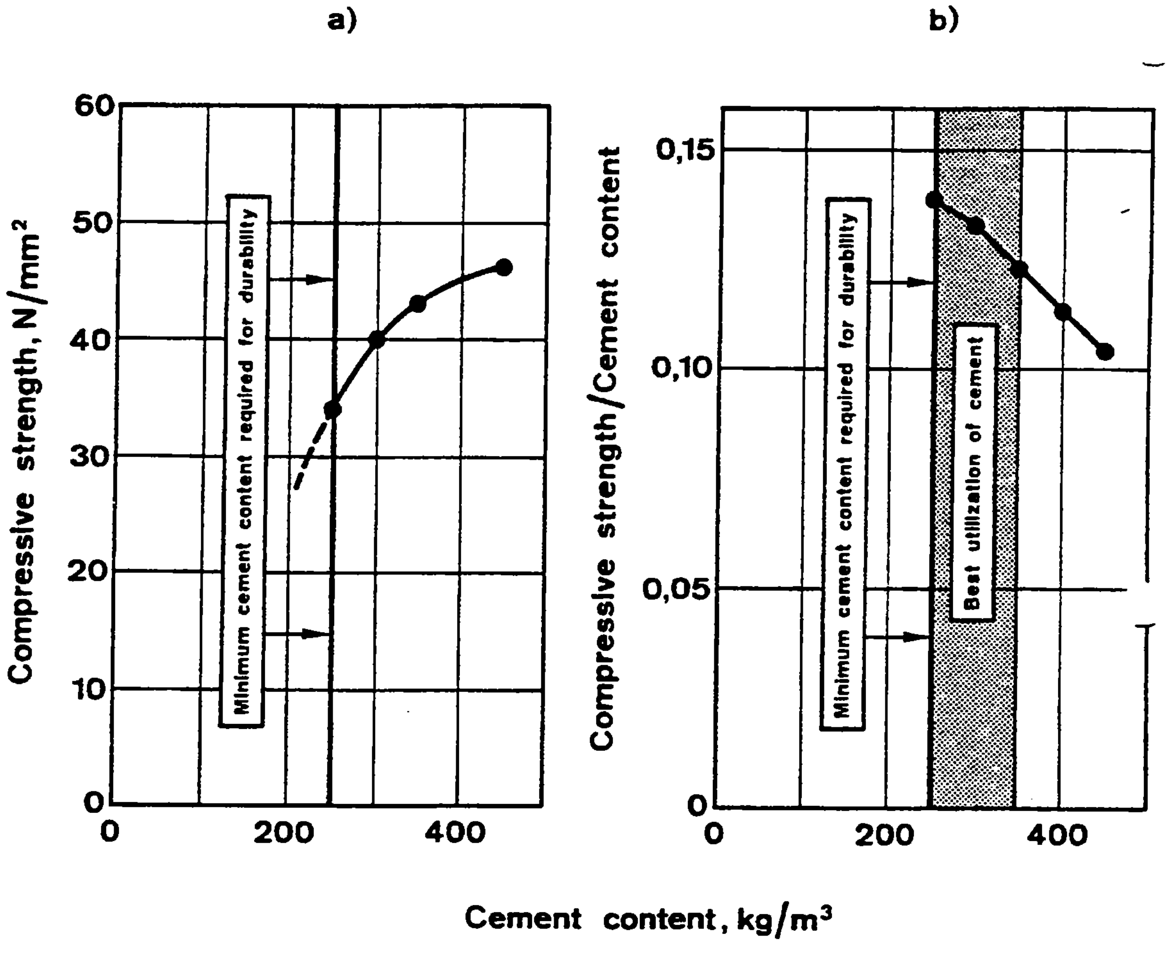
The content of cement or cement paste in concrete must be sufficient to envelop the aggregate grains in order to reduce their friction, to glue them, to fill the voids between them and also to protect the reinforcement against corrosion. Thus, an insufficient amount of cement impairs the workability and compaction of concrete and as a consequence, its strength and durability.

Note:

The cement dosage should not be below a certain minimum (usually between 250 to 350 kg/m^3 depending on the purpose of the construction) in order to guarantee impermeability and durability, even though less cement would be sufficient for the needed strength.

After all voids are filled, a surplus of cement paste does not increase the concrete strength any further since cement stone has a lower strength than aggregate (Fig. 20a). By increasing the cement content above an optimum, the ratio between compressive strength and cement content decreases (see figure). If the cement content in concrete is sufficient for full compaction, the strength of fully compacted concrete is given by the strength of the cement stone. It depends only on its w/c ratio and on the standard cement strength.

Fig. 19: Utilization of cement in concrete at constant workability



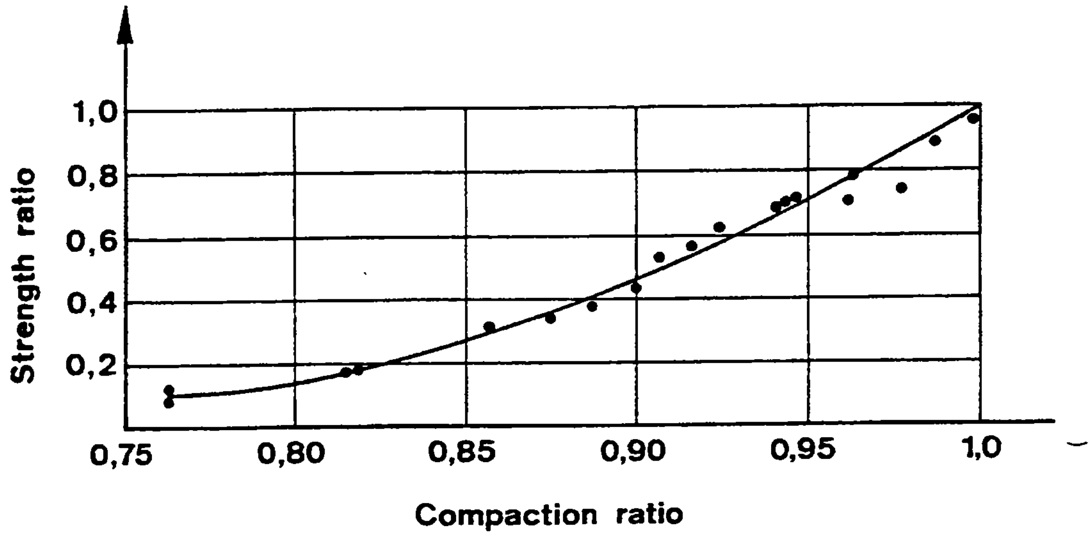
5.2.3 Aggregate/Cement ratio

The optimum **'aggregate/cement'** ratio is not only considered from a technical but also from an economical point of view since aggregate is stronger and cheaper than cement. Thus, the grading of aggregate is most important, not only for workability but also for the minimum volume of voids. It makes it possible to obtain the required strength with less cement.

5.3 Influence of handling

It is most important that the consistency of concrete permits full compaction with the tools that are available on the job site. The need for compaction becomes apparent in the following figure:

Fig. 20: Relation between strength and compaction



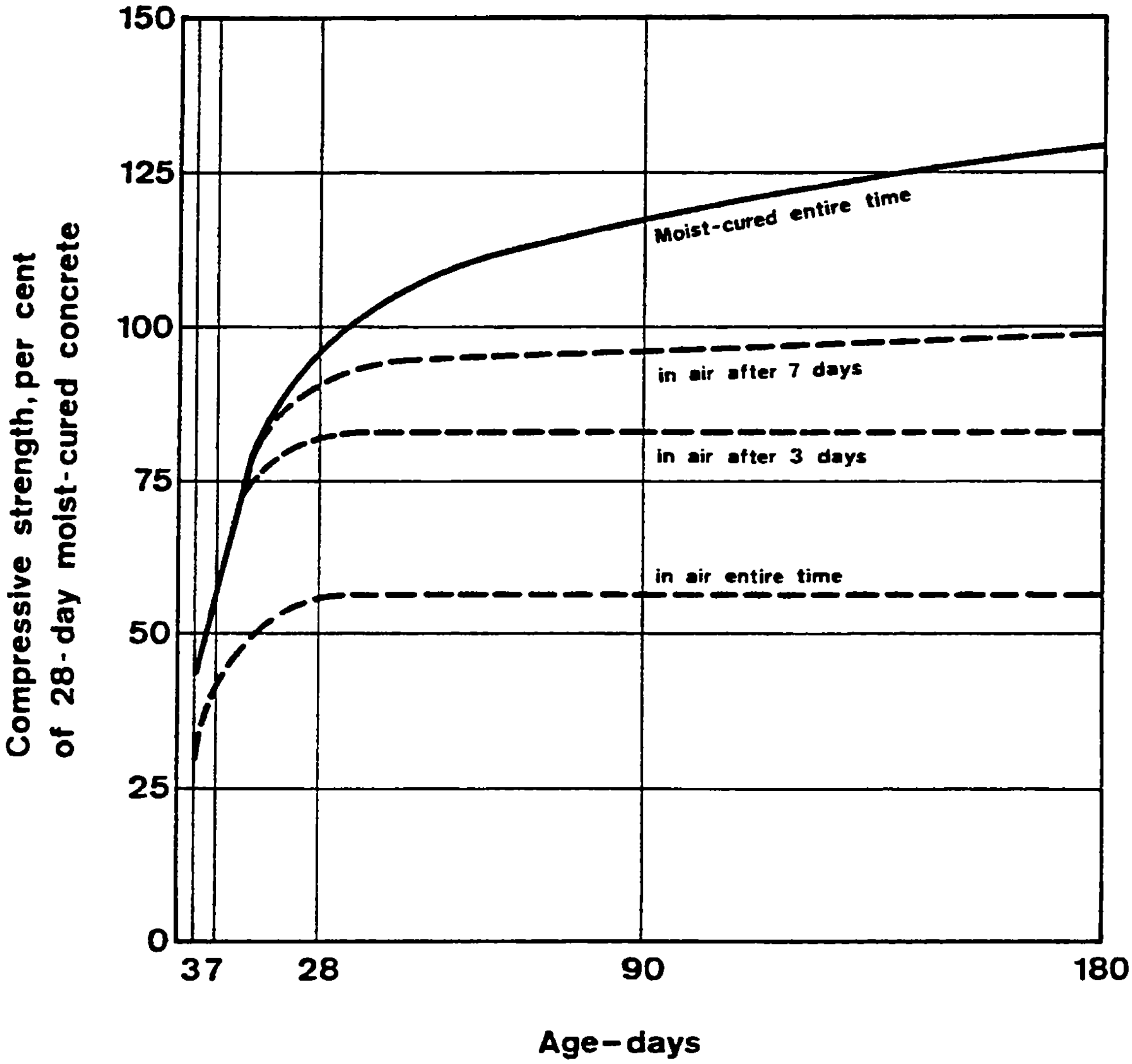
Another prerequisite for the optimum utilization of the material properties is the homogeneity of the mix. To maintain uniformity within one batch and between several batches, accurate weighing, thorough mixing and careful transporting and placing is necessary. These measures also prevent segregation.

5.4 Influences of curing

5.4.1 Moisture

After placing, the subsequent conditions strongly influence the development of the concrete properties. As for the hydration of cement water is required, loss of moisture must be prevented or even additional moisture supplied. The next figure shows how concrete strength is impaired by the lack of moisture, especially during the first 3 days.

Fig. 21: Strength of concrete increase as long as moisture is present forhydration of cement



Concrete that hardens submerged in water has the highest strength. Once it is hardened, dry concrete has higher strength than moist concrete.

5.4.2 Temperature

Higher temperatures accelerate setting and hardening of concrete, like other chemical processes(see following figures). Seasonal and even daily temperature fluctuations alter the hardening characteristics of concrete.

Fig. 22: Effect of temperatures on the compressive strength of concrete at various ages (T ≥ 20 °C)

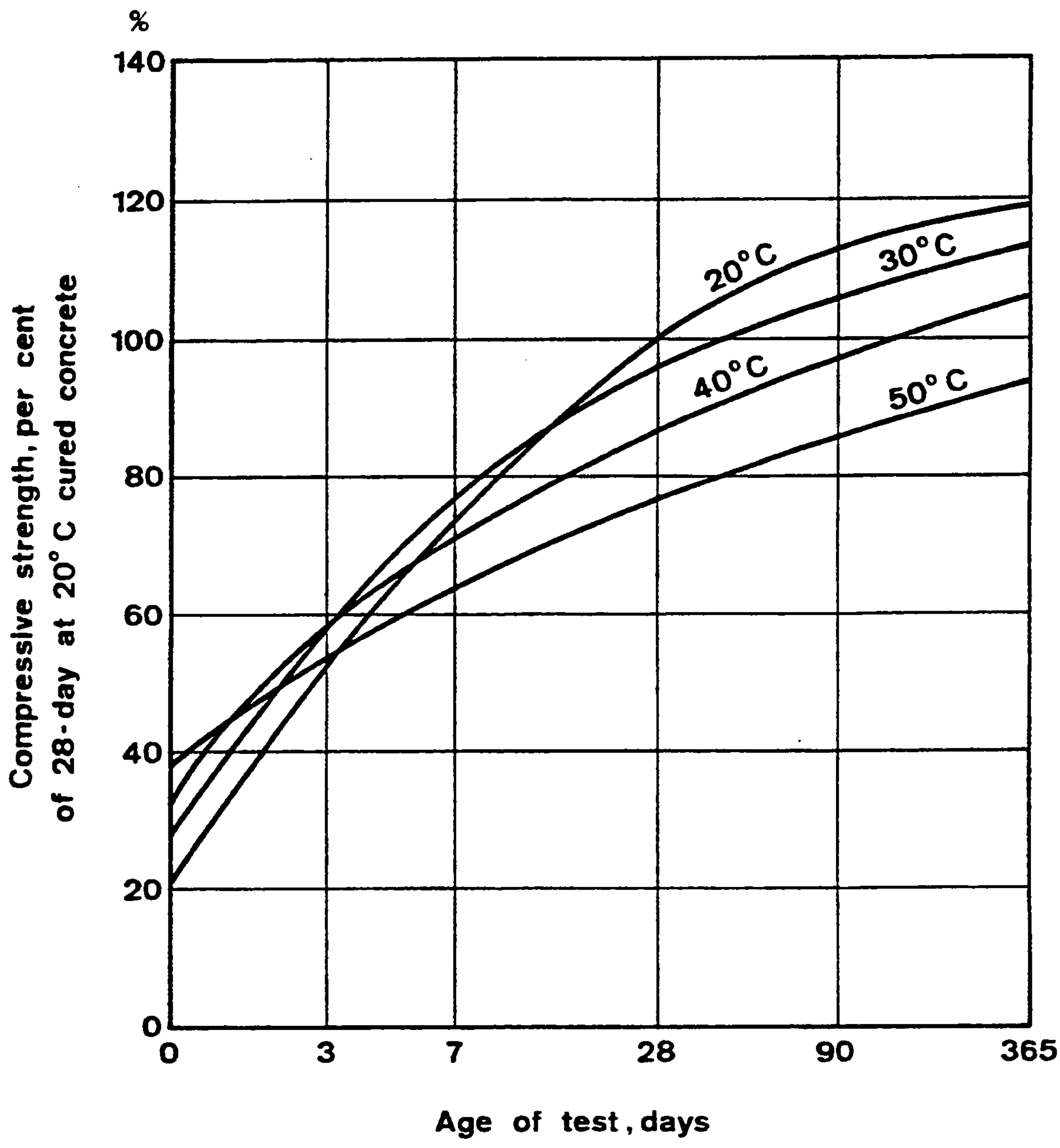
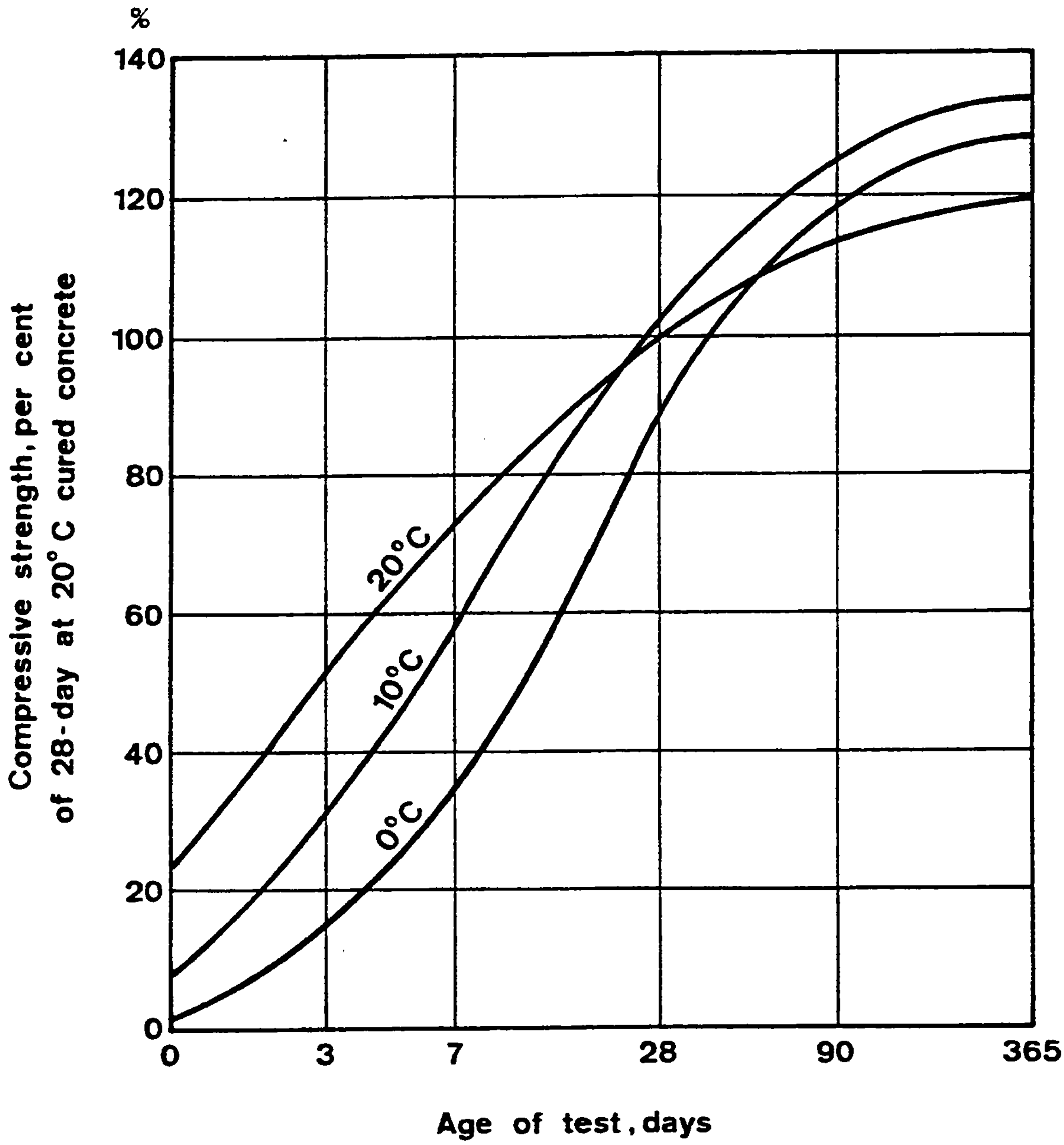


Fig. 23: Effect of temperatures on the compressive strength of concrete at various ages (T ≤ 20 °C)



Note:

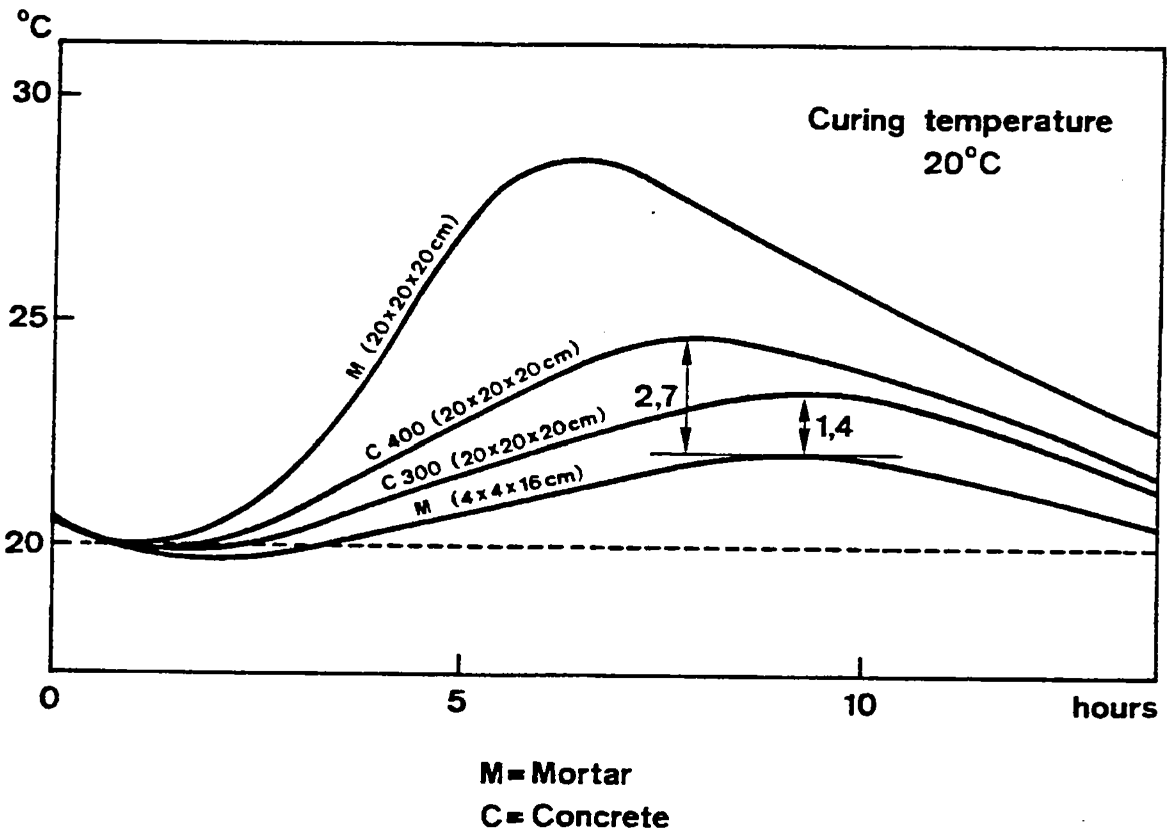
- The temperature during the first 24 hours approximately strongly affects the initial strength development of concrete and it predetermines the later hardening and even the final strength. Thus, it is futile to maintain high curing temperatures after the first 24 hours.
- Concrete cured at low temperature achieves a slightly higher final strength than the concrete cured at 30 °C or more and vice-versa.

Accelerated hardening obviously creates structures of hydration products that are less favorable for later hardening.

The effects of temperature depend not only on external curing conditions, but also on the temperature within the concrete created by accumulation of hydration heat.

The development of concrete temperature depends on cement properties, the composition of concrete and the size and shape of the concrete element. This fact is illustrated the following figure which compares the temperatures of mortar and concrete and of prisms and cubes. If concrete is protected against heat-losses and 'autocuring' takes place; some mass-concrete, the internal temperature of which may rise up to 90 °C, has to be cooled to prevent cracks caused by internal stress.

Figure 24: Temperature of mortar and concrete specimen



It is important to note that sooner or later the temperature or curing effects may activate the potential for hardening of various cements; the potential as such, however, cannot be increased by these measures.

5.5 Influences of testing methods

The influence of the testing method can sometimes be decisive for the final test result.

Specimen size, moluding, curing and testing procedure are some of the influencing factors. The above mentioned figure demonstrates how test results of temperature evolution measurements depend on specimen size and concrete composition. The differences between results on test specimens and concrete in construction can be very significant. Thus, results of specimen tests are never identical to those obtained from tests on concrete in situ. They merely give some indications. (See separate paper: 'Testing'.)

6. FACTORS INFLUENCING THE DURABILITY OF CONCRETE

In paragraph before the most important influences on concrete strength were discussed. The sum of other important characteristics of concrete in use, expressed as durability, may be related to strength in a general way, but it also affected by factors not significantly associated with strength.

Concrete must be able to endure those exposures which may deprive it of its serviceability - freezing and thawing; becoming wet and dry; heating and cooling; chemical attack by de-icing agents, sea water, salts and other substances.

Resistance to some of these may be enhanced by the application of certain ingredients or measures:

- **Alkali-Aggregate Reaction:**
  Low alkali cement, pozzolans or selected aggregate to prevent harmful expansion due to the alkali-aggregate reaction which occurs in some areas when concrete is exposed to a moist environment.
- **Sulphates:**
  Sulfate resisting cement or pozzolanas for concrete exposed to sea water or sulfate-bearing soils.
- **Abrasion:**
  Aggregate with a minimum of soft particles where resistance to surface abrasion is required.
- **Aggressive agents:**
  Use of a low water/cement ratio will prolong the life of concrete in practically every exposure-condition by reducing the penetration of aggressive liquids and gases. The water permeability also depends on the w/c ratio.
- **Freezing and thawing:**
  Resistance to severe weathering, particularly to freezing and thawing, and to salts used to remove ice, is greatly improved by the incorporation of a proper distribution of entrained air.

7. CONCLUSIONS

There are many factors which influence the properties of hardened concrete. The next figure summarizes the effect of these various factors.

Fig. 25 Factors Influencing the Properties of Concrete

PROPERTIES ↓ / FACTORS →	Cement	Aggregate	Admixture	Mix ratio	Placing	Curing	Surface treatment	Construction design
Early strength	⬤	•	◎	⬤	⬤	⬤	—	—
Final strength	⊙	•	•	◎	⬤	◎	—	—
Shrinkage	•	·	⊙	◎	•	⬤	•	—
Cracking	•	•	⊙	◎	⊙	⬤	◎	◎
Setting	⬤	—	⬤	◎	·	◎	—	—
Workability	•	◎	◎	⬤	—	—	—	—
Bleeding	⬤	⬤	⊙	⊙	•	—	—	—
Abrasion	·	◎	•	⬤	◎	◎	◎	•
Water permeability	·	⊙	⊙	⬤	⬤	◎	⊙	⊙
Freeze thaw resistance	·	⊙	⬤	⬤	⊙	⊙	◎	◎
Corrosion resistance	◎	·	•	⬤	◎	⊙	⬤	⊙
Heat of hardening	◎	—	•	⊙	—	⊙	·	⬤
Surface appearance	•	⊙	•	◎	⬤	◎	⬤	◎
Heat conductivity	—	⬤	—	⊙	⊙	—	—	•

— no effect
· very small effect
• small effect
⊙ medium effect
◎ strong effect
⬤ very strong effect

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